California High-Speed Train Project

TECHNICAL MEMORANDUM

High-Speed Train Tunnel Structures
TM 2.4.5

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Revision	Date	Description
0	29 JUL 10	Initial Release

Note: Signatures apply for the latest technical memorandum revision as noted above.

Prepared by

for the California High-Speed Rail Authority

System Level Technical and Integration Reviews

The purpose of the review is to ensure:

- Technical consistency and appropriateness
- Check for integration issues and conflicts

System level reviews are required for all technical memoranda. Technical Leads for each subsystem are responsible for completing the reviews in a timely manner and identifying appropriate senior staff to perform the review. Exemption to the system level technical and integration review by any subsystem must be approved by the Engineering Manager.

System Level Technical Reviews by Subsystem:

Systems:	*Signed document on file* Rick Schmedes	23 Jul 10 Date
Infrastructure:	*Signed document on file* Vince Jacob	22 Jun 10 Date
Operations:	NOT REQUIRED Print Name:	DD Month YY Date
Maintenance:	NOT REQUIRED Print Name:	DD Month YY Date
Rolling Stock:	NOT REQUIRED Print Name:	DD Month YY Date

Note: Signatures apply for the technical memorandum revision corresponding to revision number in header and as noted on cover.

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ABSTRACT

The purpose of this technical memorandum is to provide a reference document for:

- Direction and guidance on basic tunnel-specific design criteria for 15% and 30% design
- Technical input to the tunnel design section of design criteria being developed for the Design/Build procurement
- Technical input to the tunnel specifications that will be developed through 30% design.

This technical memorandum addresses the basic issues related to the structural design of permanent cast-in-place concrete or sprayed concrete liners for mined rock tunnels on the California High-Speed Train Project (CHSTP). These issues include design life, durability, loads and analyses. Related design considerations such as pillar stability, watertightness and drainage are addressed along with the applicability of undrained/drained and reinforced/unreinforced permanent linings.

Typical initial support arrangements, methods of construction and ground conditions are addressed in so far as they influence the design of the permanent works. Site specific initial support arrangements and methods of construction will depend on local conditions and are to be addressed by section designers. Likewise, the seismic environment is expected to be different at different tunnel sites, requiring an individual site specific assessment by section designers. Ultimately, the design-builder will undertake detailed design and select methods of construction and initial support requirements.

Seismic design criteria for preliminary design are presented in separate technical memoranda.

This technical memorandum should be used in conjunction with the following CHSTP documents:

- Memorandum on Tunnel Descriptions for Environmental Documents (March 29, 2010)
- TM 2.4.2 Basic Tunnel Configuration - which covers clearances, fixed equipment and tunnel sizes
- TM 1.1.21 Typical Cross Sections - which covers typical mined, bored and cut-and-cover single and twin track tunnels and below ground approach structures
- TM 2.4.6 Tunnel Portal Facilities - which covers sizing at grade tunnel portals to accommodate portal facilities
- TM 2.4.8 Tunnel Service and Maintenance Considerations.

Seismic design criteria for preliminary design are presented in separate technical memoranda.

1.0 INTRODUCTION

This technical memorandum addresses the basic issues related to the structural design of permanent cast-in-place concrete or sprayed concrete liners for mined rock tunnels on the California High-Speed Train Project. These issues include design life, durability, loads and analyses. Related design considerations such as pillar stability, watertightness and drainage are addressed along with the applicability of undrained/drained and reinforced/unreinforced permanent linings.

Typical initial support arrangements, methods of construction and ground conditions are addressed in so far as they influence the design of the permanent works. Site specific initial support arrangements and methods of construction will depend on local conditions and are to be addressed by section designers. Likewise, the seismic environment is expected to be different at different tunnel sites, requiring an individual site specific assessment by section designers. Ultimately, the design-builder will undertake detailed design, and select methods of construction and initial support requirements.

1.1 PURPOSE OF TECHNICAL MEMORANDUM

The purpose of this technical memorandum is to assist with the following:

- Direction and guidance on basic tunnel-specific design criteria for 15% and 30% design
- Technical input to the tunnel design section of design criteria being developed for the Design/Build procurement
- Technical input to the tunnel specifications that will be developed through 30% design.

This technical memorandum is particularly focused on the rock tunnels planned to be constructed through the mountainous terrain of the Pacheco Pass, Tehachapi and San Gabriel ranges and is also expected to be applicable for rock tunnels that are constructed along other segments of the HST alignment.

1.2 STATEMENT OF TECHNICAL ISSUE

This memorandum identifies the basic structural design parameters for the purpose of confirming technical feasibility, establishing consistent rock tunnel design elements, and preparing cost estimates for the preliminary design level.

Design of tunnel infrastructure elements shall reflect common and unique design requirements. Consistency in the design of common elements is required because all tunnels must be able to be used by high-speed passenger trains regardless of geographic location. Each tunnel shall additionally be uniquely evaluated for site-specific topographic, ground, groundwater, and seismic conditions.

1.3 GENERAL INFORMATION

1.3.1 Definition of Terms

Term	Definition
None	

Acronyms

Authority	California High-Speed Train Authority
CFR	Code of Federal Regulations
CHSTP	California High-Speed Train Project
CHST	California High-Speed Train
CIP	Cast-in-Place
HST	High-Speed Train
ID	Internal Diameter
OCS	Overhead Contact System
SEM	Sequential Excavation Method
sf	square feet

SR	System Requirement
TBM	Tunnel Boring Machine
THRSC	Taiwan High Speed Rail Corporation
TSI	Technical Specification for Interoperability of European High-Speed Lines

1.3.2 Units

The California High-Speed Train Project (CHSTP) is based on U.S. Customary Units consistent with guidelines prepared by the California Department of Transportation (Caltrans) and defined by the National Institute of Standards and Technology (NIST). U.S. Customary Units are officially used in the U.S. and are also known in the U.S. as “English” or “Imperial” units. In order to avoid any confusion, all formal references to units of measure should be made in terms of U.S. Customary Units.

2.0 DEFINITION OF TECHNICAL TOPIC

2.1 GENERAL

This technical memorandum addresses the basic issues pertaining to the structural design of permanent cast-in-place concrete or sprayed concrete linings for mined rock tunnels on the California High-Speed Train Project. This memorandum identifies the basic structural design parameters for the purpose of confirming technical feasibility, establishing consistent tunnel design elements, and preparing cost estimates for the preliminary design level. These parameters include design life, durability, loads and analyses. Related design considerations such as pillar stability, watertightness and drainage are addressed along with the applicability of undrained/drained and reinforced/unreinforced permanent linings.

This memorandum includes discussion of the following issues:

- Advantages and disadvantages of drained versus undrained rock tunnels, primarily as the drainage option relates to long term operations and maintenance requirements, and the potential increased structural requirements for a tunnel lining to be able to support full hydrostatic groundwater pressures.
- Advantages and disadvantages of reinforced and unreinforced permanent liners.

The structural design requirements are conceptually defined for both static and dynamic loading situations. The requirements are presented conceptually since the requirements must apply to a variety of ground and groundwater conditions as well as to variable topographic conditions. These conditions are anticipated to vary between different tunnel sites and regional designers shall develop these generic requirements to be compatible with site specific subsurface conditions. In addition, the seismic environment is expected to be different at different tunnel sites, again requiring an individual site specific assessment be section designers.

From a static loading conditions perspective, the structural design requirements are addressed for both geological and hydro-geological loading conditions.

Typical initial support arrangements, methods of construction and ground conditions are addressed in so far as they influence the design of the permanent works. Site specific initial support arrangements and methods of construction will depend on local conditions and are to be addressed by each regional consultant. Likewise, the seismic environment is expected to be different at different tunnel sites, requiring an individual site specific assessment be section designers. Ultimately, the design-builder will undertake detailed design and select methods of construction and initial support requirements.

Loadings will ultimately be a function of site specific ground conditions, with tunnels penetrating through fault zones (inactive for purposes of this technical memorandum), which may be composed of extremely fractured and/or decomposed materials which are likely to exhibit squeezing ground conditions, the degree being a function of both the character of the fault zone materials and the depth of burial of the tunnel. Over excavation and/or a yielding lining may be required in these conditions.

For seismic considerations, tunnels generally perform better than above-ground structures. Unlike buildings and bridges, tunnels are not inertia-driven and the tunnel deformations are controlled by the displacement of the surrounding soil medium. For loading conditions presented, acceptable structural materials are presented along with durability requirements. In addition, conventional methods of analysis for tunnel lining design are presented.

2.1.1 CHSTP Design Considerations

This technical memorandum identifies tunnel design elements to be considered and evaluated specifically for rock tunnels that are to be used exclusively by high-speed passenger trains. It is particularly focused on the rock tunnels to be constructed through the mountainous terrain of the Pacheco Pass, Tehachapi and San Gabriel ranges and is also expected to be applicable for rock tunnels that are constructed along other segments to the high-speed train alignment.

2.1.2 CHSTP Design Parameters

Design parameters for high-speed train tunnels are under development and will be defined in separate documents, including the following CHSTP technical memoranda:

- Technical Memorandum 1.1.2 - Design Life
- Technical Memorandum 1.1.10 - Structure Gauge
- Technical Memorandum 1.1.21 - Cross Sections for 15% Design
- Technical Memorandum 2.3.2 - Structure Design Loads
- Technical Memorandum 2.4.2 - Basic High-Speed Train Tunnel Configuration
- Technical Memorandum 2.4.6 - High-Speed Train Tunnel Portal Guidelines
- Technical Memorandum 2.4.8 - Service and Maintenance Requirements
- Technical Memorandum 2.9.3 - Geotechnical and Seismic Hazard Evaluation Guidelines
- Technical Memorandum 2.9.6 - Ground Motion for MCE, DBE & LDBE for 30% Design
- Technical Memorandum 2.9.10 - Geotechnical Design Guidelines
- Technical Memorandum 2.10 4 - Interim Seismic Design Criteria
- Technical Memorandum 2.10.6 - Fault Crossing Design Guidelines
- Technical Memorandum 3.2.6 - Traction Power Electrification System Requirements for Grounding, Bonding, and Protection From Electric Shock

2.2 LAWS AND CODES

Initial high-speed train (HST) design criteria will be issued in technical memoranda that provide guidance and procedures to advance the preliminary engineering. When completed, a Design Manual will present design standards and criteria specifically for the design, construction and operation of the CHSTP high-speed railway.

Criteria for design elements not specific to HST operations will be governed by existing applicable standards, laws and codes. Applicable local building, planning and zoning codes and laws are to be reviewed for the stations, particularly those located within multiple municipal jurisdictions, state rights-of-way, and/or unincorporated jurisdictions.

In the case of differing values, the standard followed shall be that which results in the satisfaction of all applicable requirements. In the case of conflicts, documentation for the conflicting standard is to be prepared and approval is to be secured as required by the affected agency for which an exception is required, whether it be an exception to the CHSTP standards or another agency standards.

There are no US codes specifically for the structural design of permanent tunnel liners. There are however several national and international guidelines which are referenced in this technical memorandum including the following publications:

Technical Manual for Design and Construction of Road Tunnels – Civil Elements – USDOT/ NHI (March 2009)

Tunnel Lining Design Guide – The British Tunnelling Society and The Institution of Civil Engineers

3.0 ASSESSMENT / ANALYSIS

3.1 TUNNELS CONFIGURATIONS

Basic configurations for high-speed train tunnels are defined in TM 2.4.2 and include:

1. Twin single-track high speed tunnels: each approximately 29.5 feet internal diameter (ID), with a pillar of ground between tunnels approximately one diameter wide at the portals, and with ground cover at the portals ranging from one-half-a-diameter to one-diameter thick. Cross-passages will be constructed for safety egress purposes to allow passenger evacuation to the portals through the non-incident tunnel.
2. Single double-track high speed tunnel: with an internal width of approximately 49 feet and with ground cover at the portals ranging from one-half-the-excavated width to the excavated-width thick. A central, fire-rated dividing wall will separate the single tunnel into two independently ventilated trackways, and safety egress will be achieved via doorways through the dividing wall. The doorways will be fitted with sliding, fire-rated doors. Passenger evacuation will be to the portals through the non-incident trackway.

3.2 ASSESSMENT

3.2.1 Analysis

The primary structural design considerations for tunnel structures are:

1. **Geotechnical Characterization.** Geological, topographical, and hydrogeological variations.
2. **Design Life and Durability.**
3. **Design Considerations.** Scope, loads, load combinations, geometric considerations, watertightness, drainage, pillar stability, portal stability, caverns, and cross passages
4. **Theoretical Methods of Analysis.**

The primary civil design elements for tunnel structures are:

1. **Principal tunnel structures.** Rock tunnel structural linings; rock tunnel portal structures; cross-passage rock tunnel structural linings
2. **Secondary tunnel structures.** Track slabs; safety walkways; ductbanks; internal tunnel dividing walls

3.3 GEOTECHNICAL CHARACTERIZATION

3.3.1 Geological Variations

3.3.1.1 Rock Types

Most tunnels are planned to traverse mountainous terrain, thus they are generally expected to be “rock” tunnels as opposed to soft ground tunnels, but in some cases, may be soft ground tunnels as alignment restrictions require. However, since the geological conditions vary throughout the length of the alignments, rock types may be entirely different not only for different tunnels but possibly also for different sections of the same tunnel. Each planned tunnel shall be evaluated in detail during design with respect to the site specific geological conditions to be encountered throughout the tunnel length during construction. Rock type and extent of weathering shall also be considered in the development of portal stabilization requirements.

3.3.1.2 Rock Structure

Depending upon the rock types expected to be encountered in any particular tunnel, rock mass discontinuities (e.g., joints, foliation planes, well developed schistosity, or bedding plane weaknesses) may be a major contributing factor to the construction term static stability of any single tunnel, to the stability of the central pillar between adjacent parallel tunnels, and to the stability of the cross passage intersections in longer tunnels. Consequently, detailed evaluation

shall be made during the design process, of rock mass discontinuity patterns, spacing and characteristics, and their implications with respect to tunnel and pillar stability and resulting implications with respect to design of the initial ground support and final tunnel lining. Although these factors may appear to be more applicable to the design of initial ground support, they are expected to influence the design of the final tunnel lining, since increased rock loads due to adverse rock structure may require a thicker final lining (and larger excavation). Rock structure and character of discontinuities shall also be considered in the development of portal stabilization requirements.

3.3.1.3 Major Structural Weaknesses

For purposes of this technical memorandum, “major structural weaknesses” are considered to be significant fault or shear zones with potentially deteriorated rock mass quality in the weakness zone, as opposed to the presence of systematic rock mass discontinuities as discussed above. These “significant” weakness zones may include both mapped features and unmapped features as may be detected during the subsurface exploration program by core drilling and/or geophysical exploration methods. These features shall be evaluated for spatial orientation, thickness, orientation with respect to the proposed tunnel alignment, and rock mass quality for assessment of excavation methods and sequences, and the development of initial ground support and final lining requirements considering the individual tunnels, the central pillar between the parallel running tunnels, and the cross passage intersections in longer tunnels. Although these factors may appear to be more applicable to the design of initial ground support, they are expected to influence the design of the final tunnel lining, since adverse ground conditions and related increased rock loads in major weakness zones may require a thicker final lining and larger excavation.

3.3.1.4 Potential Squeezing Ground

For any tunnels penetrating through high stress conditions due to high overburden, and/or through very weak rock mass materials (including fault zone materials), the potential for squeezing ground conditions shall be evaluated during the design process. If squeeze potential is identified, it shall be quantified, and implications defined with respect to determination of special methods and sequences of excavation, initial ground support requirements (both for individual tunnels, the central pillar between parallel running tunnels, the cross passage intersections in longer tunnels, and for instrumentation monitoring and verification of ground behavior during excavation), and special requirements for design of the final tunnel lining within the zone of potentially squeezing ground.

3.3.2 Topographic Variations

3.3.2.1 Variation with Tunnel Location

Similar to the geological conditions, the topographic conditions are expected to vary widely throughout the length of the alignment. Topographic conditions (and rock cover over the tunnels) may be entirely different not only for different tunnels, but possibly also for different sections of the same tunnel. It is therefore required that each planned tunnel shall be evaluated in detail during the design process, with respect to the site specific overburden conditions to be encountered throughout the tunnel length during construction. The natural hill-slope topography shall also be considered in the development of portal design details.

3.3.2.2 Variation within a Single Tunnel

For topographic conditions within a single tunnel alignment, both very shallow and very deep overburden conditions may have a significant influence on ground support requirements for both initial ground support and for the final tunnel lining. This potential influence of overburden depth, combined with geological and rock mass conditions, shall be evaluated in detail during the design process, and any implications accounted for in the final design.

3.3.2.3 Influence on Portal Stability and Design

Due to the wide variations in topographic conditions along the alignment, topographic conditions are expected to vary for different tunnel locations. In the portal zone of any particular tunnel, the topographic as well as the geologic conditions shall be considered in tunnel portal design. Flatter

natural hill-side slopes are commonly associated with weaker, less weathering resistant materials. Consequently, for such conditions, weathering is likely to be deeper than on steeper slopes, and slope instability potential failure mechanisms may penetrate deeper than for steeper slopes. These potential variations shall be considered in portal design. Tunnel alignment shall as much as possible, be perpendicular to the natural slope, within the restrictions of the overall track alignment boundary conditions, so that unbalanced loading conditions on the tunnel portal zone and slope instability transverse to the tunnel alignment can be avoided.

3.3.3 Hydrogeologic Variations

3.3.3.1 Variation with Tunnel Location

As with both geology and topography, hydrologic conditions are expected to vary widely along the planned alignment, with the result that each tunnel is likely to have site-specific hydrologic conditions that shall be considered in both portal and tunnel design. Surface water hydrology (e.g., precipitation patterns, topographic variations, vegetation type and extent of ground coverage, etc.) shall be considered for portal design, and groundwater hydrology shall be considered in final lining design. The final tunnel lining for tunnels may be drained or undrained depending on a number of factors, and the design details prepared to accommodate full, partial or nominal (in case of blockage of drains) groundwater pressure for tunnel lining design, the requirements for which may be different for different tunnels.

3.3.3.2 Variation within a Single Tunnel

It is common for the static groundwater level to vary with the topography, with topographic high areas having corresponding groundwater profile high areas. Thus within any particular tunnel, the depth of the groundwater above the proposed tunnel vertical profile is expected to vary throughout the tunnel length. The variations in this groundwater level throughout the length of any particular tunnel shall be considered in the design of the final tunnel lining, including any expected seasonal or long term variations in the groundwater profile.

3.3.3.3 Groundwater Chemistry

Site specific groundwater chemistry shall be considered for each tunnel, as aggressive groundwater may contribute to a reduction of the lining durability unless special mixtures to resist the attack of aggressive groundwater are used in the concrete for the final tunnel lining. Groundwater chemistry “normally” considered to be aggressive toward concrete durability includes but is not limited to factors such as adverse pH, high sulfate content, high chloride content, etc. Although the full waterproofing encapsulation for undrained tunnels, and the umbrella waterproofing for drained tunnels should normally limit the exposure of the final tunnel lining to groundwater, protective measure must be in place to ensure long term durability over the design life of the facility.

3.3.3.4 Hazardous and Explosive Gases

Explosive and/or hazardous gases such as hydrogen sulfide (H_2S) and methane (CH_4) present long term concerns for final tunnel lining design. For the exceptional situation of a drained tunnel, it could only be considered possibly feasible, regardless of the level of the hydrostatic head, if such gases were determined during the subsurface site investigation phase, to not be present in the groundwater. Otherwise, if gases are present in sufficiently high concentrations, only an undrained tunnel shall be considered, in which case the waterproofing membrane must also be considered to be “gas-tight” to prevent the long term infiltration of such explosive and/or hazardous gases through the waterproofing membrane into the operating tunnel. The potential presence of such explosive and/or hazardous gases shall be thoroughly evaluated as part of the detailed design process.

3.4 DESIGN LIFE AND DURABILITY

3.4.1 Design Life

The required service life of all underground structures and operational facilities is 100 years per TM 1.1.2 Design Life.

3.4.2 Durability

3.4.2.1 Groundwater Chemistry

Groundwater chemistry shall be determined for each site specific subsurface investigation for all proposed tunnels. Groundwater chemistry “normally” considered to be aggressive toward concrete durability includes but is not limited to factors such as adverse pH, high sulfate content, high chloride content, etc. Although the full waterproofing encapsulation for undrained tunnels, and the umbrella waterproofing for drained tunnels should normally limit the exposure of the final tunnel lining to groundwater, protective measure must be in place to ensure long term durability over the design life of the facility. Once groundwater chemistry is determined, appropriate mitigation measures shall be adopted for the concrete mix design to protect against the aggressive potential of the groundwater.

3.4.2.2 Atmospheric Chemistry

The quality (chemistry) of the air inside the tunnel during train operations can influence tunnel lining durability where the air in the tunnel environment contains constituents which, by interaction with exposed concrete, can produce accelerated concrete deterioration. This includes, but is not limited to phenomena such as carbonation, in which there is a chemical reaction between atmospheric CO_2 and the products of cement hydration; the attack by nitrogen oxides and nitric acid, in which leaching can take place; the attack by sulphur dioxide and sulfuric acid, in which surface deterioration is common and is accelerated in the presence of moisture and oxygen; and the formation of accumulated salt build-up on the concrete surface which can produce surface scaling. The capacity of concrete to act as a physical barrier against aggressive environmental components is critical in the degradation process, especially when steel reinforcement is being protected by concrete cover. The potential for such degradation processes shall be considered in the detailed design, including an evaluation of the operating environmental air quality within the tunnel, and the design details shall prepared accordingly in order to prevent long term concrete deterioration from the presence of such atmospheric pollutants.

System wide criteria for areas within the tunnels shall include protective measures in the detailed design of the final tunnel lining and related appurtenances:

- Material selection: Materials shall have established performance records for the service intended;
- Sealants: Sealants shall be used in crevices to prevent the accumulation of moisture;
- Protective Coatings: Barriers of sacrificial coatings shall be used on any exposed steel in the tunnel;
- Design: Use of dissimilar metals and recesses or crevices that might trap moisture shall be avoided.

3.4.2.3 Concrete Aggregate Mineralogy

Concrete aggregates to be used in any permanent concrete (or shotcrete) shall be free of any adverse constituents that could lead to the long term deterioration of the final concrete lining. Technical specifications for concrete construction shall preclude the use of aggregates having a high potential for alkalai-aggregate reaction, or any other similar adverse behavioral characteristics.

3.4.2.4 Concrete Mix Design

The mix design for permanent concrete structures shall use Type I or II cement unless site specific ground and/or groundwater condition dictate the use of Type V cement. The water/cement ratio shall be as appropriate to minimize concrete permeability, but shall be no higher than 0.45 by weight. Mixing water shall not exceed 200 ppm chloride content in the combined mixing water and admixtures combined. Concrete cover on any reinforcing steel shall be 2 inches minimum on the soil side of the lining.

3.4.2.5 Quality Assurance during Construction

A key component of successful implementation of a durable concrete tunnel lining is the field QA/QC process during construction, to ensure that the design aspects of lining durability are fully

implemented during construction. Such a QA/QC program shall be implemented during construction to monitor the successful execution of all durability related lining construction requirements.

3.4.2.6 Maintenance Implications

A key component of the long term durability of a concrete tunnel lining is the requirement for a comprehensive tunnel inspection and maintenance program. It shall be a requirement of the design process, to develop such a comprehensive inspection and maintenance program, consistent with the design and construction details, to be systematically implemented over the life of the facility.

See TM 2,4.8 - Service and Maintenance Considerations for High-Speed Train Tunnels.

3.4.2.7 Stray Current Protection

<u>Tracks</u>

At present the requirements for stray current protection electrical bonding of tunnels and underground structures have not been determined. If determined to be necessary in the future, for corrosion control mitigation, the requirements for stray current protection electrical bonding of tunnels and underground structures shall be implemented.

<u>Electrical Bonding</u>

Reference TM 3.2.6 - Traction Power Electrification System Requirements for Grounding, Bonding, and Protection from Electric Shock.

<u>Drainage</u>

The corrosion control design shall provide for stray current control at drainage facilities including conduits, manholes, junction boxes, drainage buses, cables drainage panels, and other associated equipment.

<u>QA/QC during Construction</u>

Corrosion control designs shall be coordinated with all other engineering disciplines to ensure that they do not conflict with other installations. Shop drawings, material catalog cuts, and additional information related to the corrosion control designs shall be submitted for review and approval. Testing of materials prior to their delivery from a manufacturer, or during construction, shall be conducted as required, to ensure compliance to corrosion control designs.

3.4.2.8 Corrosion Protection

The requirements for corrosion control and protection of tunnels and underground structures will be developed for final design.

3.4.2.9 Seismic Implications

There are two main aspects of seismic durability, localized lining collapse during strong ground shaking, and the requirement for a seismic joint between the tunnel (a buried structure that moves with the ground) and the portal structure that is free to vibrate. The requirement for lining reinforcement to resist localized damage during strong ground shaking was discussed above in comparing a reinforced versus an unreinforced permanent lining.

At the tunnel portal, there is an abrupt change in structure stiffness (buried underground tunnel structure versus open air unrestrained portal structure), which may subject the structure to differential movements and generate stress concentrations during seismic ground motion. The most common solution to account for this expected performance in seismic behavior is the inclusion of a seismic joint between the two types of structures. The inclusion of such a seismic joint in the design of the permanent tunnel lining and its interface with the outside portal structure is a design requirement, but the joint details require development as a function of the portal arrangement, the seismic ground motions expected, magnitude of structural movement, and the designer preferences for any particular tunnel.

The primary mitigating strategy at capable fault zones is to place the alignment at-grade with ballasted track, oriented as near to perpendicular as feasible to the fault trace, in order to minimize the fault zone length beneath the HST footprint, and allow timely inspections and repairs after an earthquake event. Buried construction at capable fault zones shall, to all practical extents, be avoided. See Technical Memorandum 2.10.6 - Fault Crossing Design Guidelines.

3.4.2.10 Fire Resistance

For preliminary design, underground facilities shall be in accordance with fire resistance requirements of NFPA 130. Fires in tunnels, depending on their type, intensity, and duration, can have significant or even catastrophic effects on the durability and structural integrity of tunnels. Tunnel structural components that could be subjected to fire in accordance with NFPA 130, including structural components of the passageways, air exhaust spaces, emergency exit stair enclosures, and interior walls shall be designed to resist structural failure when subjected to temperature rise.

3.4.2.11 Waterproofing Implications – Actual versus Contractual Leakage Rates

Waterproofing materials, installation procedures, and QA/QC inspections utilized for either drained or undrained tunnel options shall be selected, installed, and/or implemented on site to provide the contractually required level of watertightness protection of the tunnel and minimize disturbance to the static groundwater level over the full design life of the tunnel structure. Waterproofing leakage rates required by contract, and measured at the time of tunnel construction completion, shall be maintainable over the full design life of the structure without increasing as the lining and/or waterproofing system materials age and/or deteriorate with time.

3.4.2.12 Special Considerations for Permanent Sprayed Concrete Linings

Any sprayed concrete (shotcrete) linings to be utilized as a final tunnel lining, shall provide the same long term performance as a cast-in-place tunnel lining, with respect to all aspects of durability, including watertightness. Shotcrete mix designs (including w/c ratio, aggregate sizes, and admixture selection) shall be such that the potential for long term leaching of calcium carbonate is minimized. The mix design shall consider, but not be limited to consideration of such issues as:

- pH of natural water and the related lime solubility
- Anticipated long term operating temperature ranges of the tunnel, and the resulting potential impact upon lime solubility
- Minimization of shotcrete porosity and permeability without compromising the shotcrete strength, to reduce infiltration rates to satisfy contractual leakage rates and to minimize the risk of infiltrating water leaching out shotcrete component materials
- Minimize shrinkage cracking
- Require the use of alkali-free accelerating admixtures in the shotcrete
- Compliance with all relevant ACI requirements

In addition, placement procedures for shotcrete shall be selected and implemented in order to ensure compliance with all contractual watertightness and structural requirements, including but not limited to considerations such as:

- Limitations on thickness of individual shotcrete layers
- Timing of placement of the first layer considering the stand-up time of the ground
- Use of appropriate curing compounds to reduce shrinkage risk
- Use of fiber reinforcement to satisfy structural requirements and reduce shrinkage risk
- Satisfy surface roughness requirements to protect subsequent waterproofing installation
- Minimum cover over ground reinforcing elements

3.4.3 Waterproofing and Drainage

Waterproofing materials, installation procedures, and QA/QC inspections utilized for either drained or undrained tunnel options shall be selected, installed, and/or implemented to provide the required level of watertightness protection of the tunnel and minimize disturbance to the static groundwater level over the full design life of the tunnel structure.

3.4.3.1 Material Requirements

Waterproofing and drainage materials, utilized for either drained or undrained tunnel options shall be selected to provide the contractually required level of watertightness protection of the tunnel and minimize disturbance to the static groundwater level over the full design life of the tunnel structure. They shall satisfy all performance requirements, be suitable for exposure to the service environmental, and maintain the design material properties over the life of the structure. These materials shall include membranes, drainage fabric, compartmentalization water-stops, drainage and cleanout piping, any porous materials placed around the piping, and any post-installation grout materials placed to "drywall" the tunnel to correct areas of excessive leakage. These materials shall not only provide the required longevity for the material itself, but also for all bonding and splicing materials, attachment materials, and other appurtenant components. They shall be selected to aid in minimizing the potential for clogging of drains, and shall consider the longevity implications of the long term maintenance requirements. They shall be appropriately selected to be resistant to damage during storage, transportation, and installation, and during subsequent construction operations such as placement of reinforcing steel and concrete. They shall be fire retardant during the construction period.

3.4.3.2 Construction Requirements

Waterproofing and drainage installation procedures utilized for either drained or undrained tunnel options shall be implemented on site to provide the contractually required level of watertightness protection of the tunnel and minimize disturbance to the static groundwater level over the full design life of the tunnel structure. All waterproofing and drainage materials shall be installed in compliance with the manufacturer's recommendations, including but not limited to such factors as surface roughness of the substrate to which waterproofing materials are applied, the minimum number of attachment points (fixation density), the minimum amount of overlap at joints, and the orientation of joints with respect to the tunnel geometry. Care shall be taken during construction operations following the installation of drainage fabric and waterproofing membrane, to prevent damage to the membrane, including but not limited to reinforcing steel placement procedures, use of plastic on the ends of individual reinforcing bars, and use of tell-tale membrane materials (colored layer embedded within the membrane sheet) that make it easier to detect a penetration during subsequent construction operations.

3.4.3.3 QA Requirements

Waterproofing and drainage materials and installation procedures shall undergo full QA/QC inspections during all stages of the selection, procurement, installation and testing operations for either drained or undrained tunnel options. Such procedures shall be implemented on site to provide the contractually required level of watertightness protection of the tunnel and minimize disturbance to the static groundwater level over the full design life of the tunnel structure.

3.5 DESIGN CONSIDERATIONS

3.5.1 Tunnel Linings

3.5.1.1 Initial Ground Support

Final design of initial ground support will be the responsibility of the design-builder, based upon the geotechnical information contained in the Contract Documents, as well as the design-builder's plans, means and methods of underground construction. Typical initial support requirements for mined rock tunnels in good and poor quality rock are shown on Drawing 2.4.5 – A in Appendix A.

3.5.1.2 Permanent Ground Support

Permanent ground support for any mined underground excavation shall be designed for the ground and groundwater conditions for all locations within the tunnel or other structure being considered. It must be designed for the full design life of the facility without detrimental effects from external influences such as ground and groundwater loads, ground and groundwater chemistry, topographic conditions, operational conditions, and earthquake motions.

Typical permanent support requirements for drained, mined single track tunnels in rock are shown on Drawing 2.4.5 – A in Appendix A.

Reference TM 2.10.4 – Interim Seismic Design Criteria.

Lining Type

The type of lining to be implemented for any particular mined underground structure is the decision of the design-builder, provided that all performance criteria have been demonstrated to have been satisfied during the design process.

Sprayed Concrete

Sprayed concrete (shotcrete) may be used as permanent ground support for any mined underground structure, provided that it satisfies project requirements for long term excavation stability, lining durability, design longevity, lining leakage rate, and all tunnel operational requirements such as train and auxiliary equipment clearances, ventilation, drainage, lighting, fire and life safety.

Cast-in-Place Concrete

Cast-in-place (CIP) concrete may be used as permanent ground support for any mined underground structure, provided that it satisfies project requirements for long term excavation stability, lining durability, design longevity, lining leakage rate, and all tunnel operational requirements such as train and auxiliary equipment clearances, ventilation, drainage, lighting, fire and life safety.

Influence of Ground Conditions

For mined underground excavation, all contributing ground conditions throughout the length of the structure shall be considered, including the potential for wedge instability from intersecting rock mass discontinuities, potential ground squeezing in weak, intensely weathered, or otherwise disintegrated or locally crushed rock mass materials (e.g., in inactive fault zones) from stresses around the excavated opening being higher than the rock mass strength adjacent to the opening (including special zones of increased stresses such as underground intersections) and areas where the excavation width increases such as in cross over caverns, potential running ground conditions when penetrating intensely weathered, or otherwise disintegrated or locally crushed rock mass materials (e.g., in inactive fault zones), and in weathered, altered, or intensely fractured geologic materials in portal zones, including potential loading from surface landslides, rock slides or debris flows originating somewhere above the tunnel portal.

Influence of Groundwater Depth

For mined underground excavation, all contributing groundwater conditions throughout the length of the structure shall be considered, including the potential for seasonal increases in static groundwater levels, long term potential increases in groundwater levels (e.g., future reservoirs to be built above the completed tunnel) perched water above geologic aquitards, and potential variations in groundwater pressure on opposite sides of a geological fault zone.

Permeability of Lining

The permeability of the initial ground support system for any mined underground excavation is not critical, but shall be sufficiently low such that excessive groundwater infiltration through the initial lining does not preclude the successful installation of a waterproofing layer before installation of the final lining (for both undrained tunnels with full waterproofing encapsulation, and for drained tunnels which utilize only an umbrella waterproofing system terminating at the tunnel invert) as

required by the design. Water-tightness (permeability) of the initial lining applies to the entire initial lining, including all construction joints, expansion joints, cold joints, etc.

The permeability of the final lining shall be sufficiently low in order to comply with the watertightness requirements of the completed structure over the design life of the completed structure, both of which are defined elsewhere. Water-tightness (permeability) of the final lining applies to the entire final lining, including all construction joints, expansion joints, cold joints etc.

<u>Reinforcement of Lining</u>

Reinforcement of the tunnel lining for any mined underground structure shall utilize reinforcing elements that have been demonstrated during the design process to comply with all required design codes and/or applicable regulations, and all project performance criteria. For the final lining, either sprayed concrete (shotcrete) or cast-in-place concrete, reinforcing elements shall provide long term corrosion resistance in order to satisfy the durability requirements over the design life of the structure.

3.5.1.3 Interaction with Initial Support in Design of Permanent Support

The design of the permanent ground support system may assume a contribution of the initial ground support system based upon its design capacity and the structural components utilized at any point along a tunnel, at cross passages, and in crossover caverns. The method of assessing this capacity shall be approved by the Authority. The general guideline in terms of accepting an initial lining contribution to long term ground support is that only the components of the initial ground support system that may be considered to be “permanent” are those components that can be demonstrated to not be susceptible to long term corrosion and loss of structural capability. These generic criteria would normally exclude all rock reinforcement (unless fully encapsulated in a corrosion protection envelope), and any steel ribs or lattice girders not fully embedded in shotcrete or concrete. Regardless of these general guidelines, each tunnel shall be evaluated independently, and the case made on a site specific basis, for any use of the initial lining contribution to long term ground support.

3.5.1.4 Reinforced versus Unreinforced Permanent Lining

Recent observations (Japan, Taiwan, China) of structural damage to tunnel linings due to strong seismic shaking (not fault rupture or displacement across a tunnel) has been primarily associated with unreinforced portions of the concrete lining in tunnels subjected to strong ground motion. Sections of tunnel lining that were reinforced exhibited far less damage during strong ground motion. It is likely that the permanent tunnel lining, whether cast-in-place concrete, or sprayed concrete (shotcrete) will be reinforced to resist seismic loads

It should be noted that the terminology “ground motion” as used for purposes of this technical memorandum is intended primarily to address shaking type ground motions experienced by a tunnel from seismic activity along an active fault within the regional influence zone of that active fault, not from seismic activity along an active fault actually crossing a tunnel. The CHSTP alignment is not permitted to cross active faults in tunnel.

3.5.2 Loads

3.5.2.1 Static Loads

Static loads to be incorporated in the design of the final lining of all underground structures include all non seismic and non train vibration related loads. These are described in TM 2.3.2 – Structural Design Loads. In addition, any loads that may be introduced by the particular details of the design-builder’s selected means and methods of construction shall be accounted for in the design process.

<u>Earth Loads</u>

Earth loads to be accounted for in the design of the permanent lining of all mined underground structures, shall properly and fully account for all potential geological long term contributing factors such as gravity (assuming some arching as allowed by the site specific ground conditions), rock structure orientations, spacings, and character, natural and structure induces (stress concentrations) stresses in the ground over and adjacent to the underground structure,

and any potential squeezing loads that may be produced by the ground adjacent to the opening being overstressed by the creation of the opening or any adjacent openings (e.g., parallel tunnel) or underground intersections (e.g., cross passages) intersections.

Groundwater Loads

Groundwater loads shall represent the full static groundwater levels to be expected along the tunnel alignment at any particular location along the length of any particular tunnel, unless the Authority has pre-approved a drained tunnel at any particular location. Should a drained tunnel be required for “extreme” groundwater conditions that would otherwise require an excessive lining thickness for an undrained structure, the designer shall prepare a proposed reduced lining design water pressure.

3.5.2.2 Dynamic Loads

Dynamic loads to be incorporated in the design of the final lining of all underground structures include all seismic and all train vibration related loads. These are outlined in TM 2.3.2 - Structure Design Loads and TM 2.10.4 - Interim Seismic Design Criteria.

Train Loads

Dynamic loads from trains operation in any underground openings shall be accounted for as required by TM 2.3.2 - Structure Design Loads and TM 2.10.4 - Interim Seismic Design Criteria.

Surcharge Loads

Surcharge loads from any existing or planned structures that overly and/or are adjacent to the mined underground structures, and whose ground pressure (shallow or deep foundations) extends to tunnel location and depth, shall be accounted for in the design of the final lining.

Seismic Loads

Seismic loads to be considered in the design of the final lining of all underground structures shall be in compliance with the requirements presented in TM 2.3.2 - Structure Design Loads and TM 2.10.4 - Interim Seismic Design Criteria. It shall also be a design requirement that all anticipated seismic distortions to both underground and portal structures resulting from a “design earthquake” shall be evaluated for structural stability for that level of performance per the requirements of TM 2.10.4.

3.5.3 Load Combinations

Load combinations to be considered in the design of final linings for all mined underground structures are as defined in TM 2.3.2 - Structure Design Loads.

3.5.3.1 Applicable Codes

Design codes applicable to the design of final linings for all mined underground structures are as defined in TM 2.10.4 - Interim Seismic Design Criteria.

3.5.4 Geometric Considerations

3.5.4.1 Tunnel Fixed Equipment

Tunnels are required to provide sufficient provide space for all necessary fixed equipment.

Conceptual design drawings have been developed to illustrate various types, and typical arrangement and locations of continuous and intermittent fixed equipment and the supporting tunnel structure. These drawings are included in TM 2.4.2 - Basic Tunnel Configuration and should be read in conjunction with typical tunnel cross sections included in TM 1.1.21 - Typical Cross Sections. Arrangements and locations will vary at tunnel enlargements, niches, cross passages and interfaces with other tunnel and structural sections.

3.5.4.2 Tunnel Clearances

The tunnels are required to allow sufficient clearances for necessary fixed equipment and rolling stock.

Dimensions for static and dynamic envelopes in the tunnels are the same as for other structures and development is documented in TM 1.1.10 - Structure Gauge.

For design and performance requirements with respect to tunnel clearances, see TM 2.4.2 – Basic Tunnel Configuration for reference.

3.5.4.3 Tunnel Size

For design and performance requirements with respect to tunnel size, see TM 2.4.2 – Basic Tunnel Configuration for reference.

3.5.4.4 Tunnel Shape

For all design and performance requirements with respect to tunnel cross section shape see TM 2.4.2 – Basic Tunnel Configuration for reference.

3.5.4.5 Invert Requirements

For mined structures where there is a non-circular invert shape considered, stress concentrations may occur in the lining at locations of perimeter geometry such as the invert where the sidewall perimeter profile merges with the invert profile. If in the preliminary design of the initial and final lining, the combination of ground and groundwater loads applied to the structure, create excessive stress concentrations in the lining at this merge point between perimeter profiles, the lining shape may need to be modified to reduce these stresses to an acceptable level. This may have particular application where squeezing ground is considered, with high horizontal pressures and potential invert heave, and/or where an undrained lining has hydrostatic groundwater pressures that are sufficiently high to produce similar stress concentrations.

3.5.5 Watertightness and Drainage

3.5.5.1 Considerations

A number of factors shall be considered when evaluating the watertightness and drainage aspects of any particular mined underground structure, as outlined below.

Groundwater Depth

The height of the static groundwater level above the tunnel crown, including any anticipated seasonal and/or long term variations, shall be considered in making the determination and/or recommendation of whether or not a mined underground should be designed as a drained structure or an undrained structure. Factors that contribute to this determination/recommendation shall include but not be limited to:

- Rock mass permeability and risk of long term groundwater drawdown for a drained structure.
- Recharge rate to the underground hydro-geological regime from surface precipitation.
- Magnitude of the long term groundwater pressure that must be designed for, and the structural requirements (and related cost implications) to resist this “design” groundwater pressure.
- Site specific groundwater (and ground) chemistry, and its related potential for clogging of drainage features with calcium precipitates over the design life of the mined underground facility.
- The possible presence of dissolved toxic or explosive gases that could be released into the tunnel environment should the groundwater be present within the operational tunnel features for a drained tunnel.
- Long term operations and maintenance considerations (both effectiveness and cost) for a drained tunnel, considering the groundwater chemistry (and initial tunnel lining chemical dissolution potential) and its potential for excessive carbonate buildup in the drainage system. A cost benefit analysis shall be performed in order to help in making lining drainage requirement determinations in cases where only marginal benefits would be gained by the requirement for an undrained final lining for a particular mined underground structure.

Groundwater Chemistry

It shall be a requirement that groundwater chemistry be considered during the design process, as it may influence the design and the long term performance characteristics of the waterproofing and drainage provisions of tunnels. Although all dissolved solids and gases in the groundwater shall be evaluated and considered, of particular concern for design of the waterproofing and drainage system is the presence of dissolved calcium carbonate, which can come out of solution due to changes in pressure and/or temperature as groundwater passes into the drainage system, often complicated by contact of the infiltrating groundwater with air and/or the loss of carbon dioxide in the process. In such conditions, the calcium carbonate forms a precipitate on any contact surfaces, and the clogging potential for this precipitate on waterproofing and drainage components of the final lining design shall be fully evaluated and accounted for in the design. A related phenomenon is the leaching of calcium carbonate out of porous construction materials such as shotcrete or concrete as the groundwater passes through them. This process is a function (in addition to the other factors noted above) of the carbon dioxide content, the pH, both of which influence the solubility of calcium carbonate in water, This potential leaching process shall also be evaluated in the design process, and accounted for in the design details of the waterproofing and drainage system components.

Dissolved Gases

The potential for the presence of dissolved noxious or explosive gases dissolved in the groundwater at any particular tunnel site shall be evaluated as part of the detailed subsurface investigation. If a positive gas presence indication is determined, then the waterproofing system shall also be impermeable to the passage of gases through the waterproofing system. Also, if a positive gas presence is determined, then only an undrained tunnel design shall be considered acceptable, to prevent the possibility of noxious or explosive gases ever entering the operating tunnel.

3.5.5.2 Requirements

Waterproofing

Waterproofing as a critical component of the final lining of any mined underground structure will be required for all such structures. The determination whether or not this waterproofing shall provide full or partial encapsulation will be a function of the decision on the requirement for a drained or an undrained final lining. A drained final tunnel lining would require only umbrella waterproofing over the top arch, invert to invert. An undrained final tunnel lining would require full encapsulation by the waterproofing layer.

Typical waterproofing arrangements for drained, mined single track tunnels in rock are shown on Drawing 2.4.5 – A in Appendix A.

For any waterproofing system, whether it be the drained umbrella system or the undrained full encapsulation system, the waterproofing system shall be compartmentalized by water barriers incorporated into the waterproofing membrane, installed at intervals ≤50m (~165 feet). Waterproofing and drainage materials applied to the exposed surface of the initial lining system shall be flame-proof for safety. The membrane shall incorporate a colored embedded ”tell-tale” layer to reveal any membrane penetrations made during final lining reinforcement placement, so that they can be repaired before the final lining is placed.

Drainage

For an undrained final tunnel lining, no separate leakage-specific in-tunnel drainage system will be required. Any minor amount of groundwater infiltration through the final tunnel lining, if in compliance with the project leakage limits as defined below, can be handled by the inside tunnel drainage system, which will be designed to collect and divert, water shed of trains when passing through the tunnel, outside precipitation draining into the tunnel from the portal areas, and water (or foam chemicals) used in emergency response to a fire incident within the tunnel.

The minimum incline of drainage systems shall be ≥0.3% towards a portal. The minimum drain pipe diameter shall be 300mm (~12 inches). Drains shall be accessible for maintenance and

cleaning at intervals ≤50m (~165 feet). Longitudinal drains for tunnel water shall be placed at the low point of the invert.

For a drained tunnel, a separate use specific drainage system at the case of the tunnel arches, shall be designed to collect and divert all infiltrating seepage water which has been diverted to the invert drains by the umbrella waterproofing system.

Typical drainage arrangements for drained, mined single-track tunnels in rock are shown on Drawing 2.4.5 – A in Appendix A.

3.5.5.3 Maintenance Implications

Drained versus Undrained

There are several factors to be considered when making the decision about whether or not a final tunnel lining should be drained or undrained. These factors include but are not limited to initial construction cost, long term operations and maintenance costs, potential water drawdown, and potentially increased structural requirements resulting from the requirement to design for full hydrostatic water pressures. The reliable functioning of tunnel waterproofing is particularly important for transportation tunnels due to the access restrictions for inspection and maintenance during tunnel operations. A waterproofing system must represent the optimal solution between the desired performance requirements, and the technical and economic considerations. In many cases, the cheapest solution may not represent the most economical one, once operations and maintenance costs over the life of the structure are considered. The relatively low additional costs of a good waterproofing system usually have a positive effect over the life of the structure.

The concern for groundwater drawdown is a concern for many projects where drained tunnels are either planned or built. For a drained tunnel with a low leakage rate, the groundwater drawdown influence zone may be small, even though the tunnel functions as a drain, albeit a “slow” drain. Considering the above discussions, it should noted, that even if a drained tunnel does draw down the static groundwater level, that drawdown has limits to its influence zone as with conventional drawdown. All of these technical considerations shall be included as part of the overall design/decision process when deciding whether a tunnel should be drained or not.

Influence of Groundwater Chemistry

It is a common problem in many tunnels, that there is a clogging risk of tunnel drainage systems due to the deposition of calcium carbonate deposits. Systematic tunnel inspections over the early years of tunnel operations for several transit systems, has revealed that tunnel waterproofing and drainage were critical, with potential threats to tunnel stability as tunnel drains became clogged with calcium carbonate deposits building up over time in the drainage system, with consequent build-up of hydrostatic pressures on the tunnel lining when the tunnel had been initially designed as a “drained” structure. One of the primary conclusions was that the inclusion of a drainage fabric layer in the lining of a sequentially mined tunnel (SEM or NATM) could be a key element in keeping hydrostatic water pressures under control for structures designed to be “drained”, provided that the drainage system could be kept open and operational over the life of the structure. It shall therefore be a design requirement that long term maintenance implications resulting from potentially adverse groundwater chemistry, be fully evaluated so that the waterproofing and drainage design elements reflect provisions to minimize long term maintenance requirements and related operational costs.

Cost Implications

As a consideration in the decision process of having a drained versus an undrained tunnel it is inevitable that cost will be a driving force (in addition to technical factors), if not the determining factor. Cost considerations during the design evaluations shall include not only the initial capital cost of construction, but also the long term costs of operations and maintenance, which can be considerable if the drainage system of a drained tunnel require frequent cleaning. Another cost consideration, although it is an intangible cost, is the cost of disruption of tunnel service if the tunnel must be closed, or have limited shut-down periods, in order to allow the maintenance and cleaning of the tunnel drainage system to be performed. The higher construction costs of an undrained tunnel often constitute an argument in favor of the decision to build a drained tunnel

instead. Additional cost considerations, which shall be considered when making the design exception decision about the type and extent of tunnel drainage, are noted below:

- A substantial part of the expenses of tunnel maintenance and repair are a result of mistakes and errors during design and construction. Most of the time, this is influenced by the fact that those involved in design and construction, have little or no experience with the problems of maintenance and its costs.
- Over the service life of a tunnel, the required efforts for tunnel maintenance resulting from the adoption of a drained waterproofing system can become quite large. The performance of a Life Cycle Cost analysis for both tunnel drainage options, sometimes concludes that in spite of the higher initial construction costs, an undrained tunnel is the more cost effective overall solution. This observation can sometimes be problematic, if the construction costs and the maintenance costs come out of different budgets, without being combined in order to obtain a broader overall cost perspective.]
- The higher maintenance costs of drained tunnels are usually attributable to the build-up of calcium deposits in the drainage piping system, requiring a high level of both technical effort and logistical planning for an operational tunnel.
- The problem of drainage pipe calcification, is often amplified by design and construction decisions and actions such as: use of unsuitable drainage materials, poor quality control and inspection when installing the drainage system, and unsuitable inspection and maintenance methods and unfavorable maintenance intervals.
- Significant factors which contribute to the development of increased tunnel operational costs include: the systematic removal of carbonate build-up increases the cost of tunnel operations, the service life of the drainage pipes may be reduced due to the abrasive action of the cleaning methods and/or tools, the periodic requirement to temporarily close a tunnel to allow systematic maintenance operations to take place.

3.5.5.4 Acceptable Leakage Rates

Short Term

Short term groundwater infiltration rates as they apply to the design of the final lining, will be related primarily to allowable seepage through the initial tunnel lining, and its impact upon the ability to install the final waterproofing layers on the initial tunnel lining before installation of the final tunnel lining. Such infiltration rates will be as determined by the manufacturer's recommendations for the particular waterproofing materials being considered at any particular tunnel.

Long Term

The allowable long term seepage through the final tunnel lining has not yet been determined. Underground connecting facilities such as cross passages are required to satisfy the same watertightness criterion as the mainline tunnels.

3.5.6 Pillar Stability

3.5.6.1 Influence of Rock Quality

Rock quality can have a major impact upon pillar stability, with lower rock mass quality having lower rock mass strength. This potential must be considered when evaluating pillar stability between parallel running tunnels, especially where the pillar is less than one excavated diameter in width, and where the overburden is relatively high, and where the ground may be weak due to poor induration, weathering, intense fracturing or crushing, etc. In such weak ground conditions, increased pillar reinforcement may be required during construction, and the potential impact of these weak ground conditions upon the final tunnel lining shall be checked and fully accounted for in the detailed design process.

3.5.6.2 Influence of Discontinuity Patterns and Characteristics

Even if the rock mass is of relatively good quality, rock mass discontinuities may form potentially loose wedges that if allowed to displace out of the pillar, reduce the pillar overall strength sue to the reduction in bearing area. This potential must be considered when evaluating pillar stability

between parallel running tunnels, especially where the pillar is less than one excavated diameter in width, and where rock mass discontinuities are well established and form kinematically possibly wedge failures. In some cases, it may be required to install pre-support in the pillar from the first tunnel, before driving the second tunnel, so that concentrated loads from loose wedges do not come on the final lining.

3.5.6.3 Influence of Tunnel Size

As tunnels get wider, especially as poor ground is encountered, the excavation size usually increases in order to allow more robust initial ground support, and final lining to be installed without infringing upon the operational train clearances within the tunnel. This becomes a more critical issue as the track spacing between tunnels remains the same, but the tunnel excavations become wider. The potential for overstressing the central pillar under such conditions shall be fully accounted for in the development of the required means and methods of construction, and the potential impact of these means and methods upon the performance of the final tunnel lining.

3.5.6.4 Influence of Tunnel Spacing

For a fixed spacing between track centerlines, the pillar width between the excavated perimeter surfaces of the two parallel tunnels, should “normally” be kept at a minimum of the equivalent of one excavated tunnel width. Even with this minimum width, the vertical stress concentrations of the two tunnels overlap, creating vertical stresses in the pillar higher than they would have been for an individual tunnel. This is especially critical where the ground may be weak as in fault zones, producing a relatively weak pillar; and/or where the tunnels have a high overburden producing high stresses in the central pillar regardless of pillar strength. Where either or both of these conditions apply, the track spacing and pillar spacing shall be checked to validate whether or not the planned tunnel spacing is wide enough to permit excavation of both tunnels without inducing a pillar collapse and/or tunnel failure. The long term loads on the final tunnel lining, resulting from such a potential pillar failure, shall be fully accounted for in the detailed design process.

3.5.6.5 Influence of Tunnel Depth

For longer tunnels, with potential increasingly high overburden above the tunnels, the influence of these high overburden loads shall be fully accounted for in the design of the final tunnel lining. This would be especially critical where the ground in the central pillar may be weak, intensely fractured, or otherwise unable to carry loads without supplemental ground support. Under these conditions, the long term loads on the final tunnel lining, resulting from potential high pillar stresses, shall be fully accounted for in the detailed design process.

3.5.6.6 Influence of Intersections

Where tunnels are of sufficient length that NFPA fire-life safety regulations require cross passages between adjacent parallel running tunnels. Under these circumstances, the introduction of the cross passage further complicates the stress distribution in the pillar, with even higher stresses in the pillar adjacent to the pillar cross passage, than the pillar without the cross passage. In addition, the creation of the cross passage introduces an additional free face, toward which unstable wedges could fail, under the driving forces of the increased stress concentrations at the tunnel – cross passage intersection. During the design process, the potential failure mechanisms during cross passage excavation, shall be evaluated, and construction means and methods developed to preclude failure, and cross passage linings designed to withstand all induced loads resulting from the three dimensional stress concentrations at the intersection. In addition, the final tunnel lining requirements adjacent to the cross passage intersection shall be checked for satisfactory performance under the potential increased loading resulting from the presence of the cross passage intersection.

3.5.6.7 Acceptable Factor of Safety

<u>Calculation of Pillar Strength</u>

Pillar strength evaluations at any particular place along a tunnel alignment, shall consider all contributing parameters, including but not limited to pillar geometry (W/H), rock type, rock mass discontinuities (orientation, spacing and frequency), degree of weathering, etc.

Calculation of Pillar Stress

Stress calculations in the central pillar between adjacent running tunnels at any particular location along a tunnel alignment, shall consider all contributing parameters, including but not limited to pillar width, overburden depth, underground intersections, surcharge loads, etc.

Construction Term versus Long Term

The Factor of Safety against failure of the central pillar between adjacent running tunnels at any particular location along a tunnel alignment shall consider the applied stresses at that location, as well as the pillar strength at that location.

3.5.7 Portal Stability

3.5.7.1 Influence of Nearby or Overlying Construction

The design of the portal for any particular tunnel shall consider the potential influence of any existing or planned overlying and/or adjacent structures over the portal, and the portal design m shall accommodate any loadings from these nearby structures.

3.5.7.2 Influence of Rock Type

The design of the portal structure for any particular tunnel shall consider in detail, the type geological conditions in which the portal will be constructed. As a minimum, the portal structure evaluations shall consider such issues such as:

- Rock and/or soil type
- Influence of near surface weathering upon strength and deformation properties of portal zone geological materials
- Influence of discontinuity patterns and characteristics upon slope stability
- Rock-fall considerations and protection requirements above the portal
- Landslide and surficial debris flow risk above the portal

3.5.7.3 Influence of Near Surface Weathering

The in-situ weathering upon portal cut stability at any particular portal site shall be fully evaluated in the design process, considering such factors such as rock type, topography, and surface and subsurface drainage. The extent of and the depth of weathering shall be considered in developing the required depth of the portal cut and the long term stability of the slope above the portal cut.

3.5.7.4 Influence of Discontinuity Patterns and Characteristics

The influence of rock mass discontinuity patterns, spacing, and characteristics, upon portal cut stability at any particular portal site shall be fully evaluated in the design process, considering such factors such as rock type, topography, and surface and subsurface drainage. The extent of and the depth of weathering shall be considering in developing the required depth of the portal cut and the long term stability of the slope above the portal cut. The evaluations shall include both static and dynamic loading conditions.

3.5.7.5 Rock-Fall Considerations and Protection Requirements

The possibility of the localized failure and/or loosening of individual rock blocks (by sliding [planar or wedge] and/or toppling) above the tunnel portal structure shall be evaluated. If such a risk is identified as being plausible, design and construction provisions shall be developed during the design process for stabilization of such potentially loosened blocks. Solutions may include but not be limited to some combination of block removal, tie backs, rock-fall safety nets, trenches, and improved surface water drainage (collection and diversion of runoff away from the portal structure). The evaluations shall include both static and dynamic loading conditions.

3.5.7.6 Landslide and Surficial Debris Flow Risk

The possibility of the localized failure and/or creep of near surface geological materials above the tunnel portal structure shall be evaluated. These types of failure potential shall include but not be limited to landslides (new or reactivated), debris flows, lateral spreading, and localized slumping, or some combination of these failure mechanisms, If such a risk is identified as being plausible,

design and construction provisions shall be developed during the design process for stabilization of such potentially threatening earth instability. Solutions may include but not be limited to some combination of block removal, tie backs, rock-fall safety nets, collection trenches, and improved surface water drainage (collection and diversion of runoff away from the portal structure). The evaluations shall include both static and dynamic loading conditions, and the potential influences of short and long term precipitation events that could increase the pore pressures within the potentially loose earth mass, and thereby reduce the factor of safety against failure.

3.5.7.7 Minimum Rock Cover

The minimum acceptable rock cover over the portal structure shall be ½ tunnel diameter, unless the topography is so flat that such a geometric criterion is impractical. In such a case, each site shall be considered separately as a “special case”. In all cases, the portal zone is likely to be in more weathered near surface materials, which are inherently weaker than intact unweathered rock. These “weaker” materials shall be characterized on a site specific basis, and detailed evaluations made with respect to potential slope instability when the portal cut is made. Any potential risk of slope instability shall be remedied by appropriate earth reinforcing systems that provide an adequate Factor of Safety for both static and dynamic loading conditions.

3.5.7.8 Potential Ground Surface Settlement

It is common experience that more lost ground during tunneling occurs at the start of excavation operations, especially in weak and/or weathered materials, typical of what may be expected at the tunnel portal turn-under where actual tunnel excavation will begin. This will be critical for installation of initial ground support, but if loosening of the ground is allowed to develop during the excavation process, then the increased loading will have to be carried, at least in part, by the final tunnel lining. If such loosening and/or excessive lost ground resulted in the development of a chimney to the surface in the portal area, the final lining may be required to carry full overburden loads, depending upon the geological conditions and the methods of remediation of the chimney and the accompanying ground surface settlement.

3.5.7.9 Sidehill Unbalanced Loading

In the event that the topographical restrictions, combined with track alignment requirements, will not allow the portal to be aligned near parallel to the sidehill contours, a portal at a skewed angle to the sidehill contours may be produced as a compromise. In such a case, asymmetrical loading on the tunnel portal area may be a result, and this adverse situation shall be analyzed for this loading situation, and any special requirements for sidehill reinforcement incorporated into the portal design in order to reduce or eliminate the unbalanced loading conditions.

3.5.7.10 Influence of Seismic Loading (Shaking and/or Distortion)

Seismic design criteria for all tunnel structures are addressed in TM 2.10.4 - Interim Seismic Design Criteria. The design of the tunnel portal structures and final tunnel lining, and the design of a seismic joint between the portal structure and the buried tunnel structure, shall be in compliance with the requirements of these TMs, including the evaluation of the dynamic slope stability for slopes above the portal structures, and the design of appropriate earth retaining systems under seismic loading conditions. At the structural connection between the buried tunnel structure, and the exposed portal structure, a seismic joint shall be designed and constructed, in order to accommodate any differential ground movements during an earthquake, between the buried structure and the portal structure. This connection shall be able to accommodate any combination of the longitudinal displacement (compression or tension), shear displacement (any direction in a plane perpendicular to the tunnel alignment), and torsional rotation (any direction in a plane perpendicular to the tunnel alignment, between the two adjacent tunnel structures. The amount of each type of displacement to be accommodated by the seismic joint, and the potential combination of movements, shall be based upon a site specific evaluation at each individual tunnel, accounting for the ground conditions and anticipated ground behavior at that tunnel location, and the estimated ground motions to be experienced by the tunnel and portal structures from the “design earthquake” at that particular tunnel. The seismic joint shall be constructed of appropriate materials to satisfy all contractual longevity requirements, as well as being able to

accommodate the estimated differential ground motions without material rupture or other distress that would limit its subsequent ability to perform its intended seismic function.

3.5.7.11 Influence of Surface Water Drainage and Vegetation Cover

Surface waste drainage from above and beside the tunnel portal shall be collected and diverted away from the portal structure, and shall be implemented in such a fashion as to minimize surface erosion, utilizing vegetation plantings if required to reduce erosion potential.

3.5.7.12 Influence of Train Aerodynamics

The details of portal design as a function of train operations (provisions for sonic boom, tunnel length influence, and length of the pressure relief structure) are addressed in TM 2.4.6 Tunnel Portal facilities and TM 2.4.2 Basic Tunnel Configuration.

3.5.7.13 Influence of Topography

The portal area shall be graded as closely as possible to match the pre-construction contours, and the tunnel portal structure shall be as close as possible parallel to the post-construction ground contours.

3.5.8 Crossover Caverns

3,8.5.1 General Considerations

The requirement for crossover structures between adjacent tracks will be a function of the final track alignment developed during the design process, considering contributing factor such as space available for crossovers outside the tunnels, which may be limited in some cases where a viaduct aerial structure connects directly to a tunnel without any at-grade track alignment in between. In such a condition, the track crossover may be required to be underground, incorporated into the tunnel structure. Where the planed twin parallel single track tunnels are utilized, this would require that the two tunnels merge into a single structure without the benefit of a central rock pillar for structural stability. This will require that the larger underground opening be designed for the same operational and performance criteria as for the single track tunnels, and for the site specific boundary conditions (geology, hydrogeology, topography, and seismic) applicable at the tunnel where the underground crossover structure is required. The development of the detailed design of the final lining of the enlarged structure shall account for the size influences of contributing geotechnical factors including but not limited to rock mass quality in the crossover area, overburden depth over the crossover, groundwater height above the crossover, required track spacing and related required opening width to achieve the required rolling stock clearances with the excavation perimeter, and the three dimensional stress influences of the twin tunnel intersections at each end the enlarged single crossover excavation.

3.5.9 Cross Passages

3.5.9.1 Influence of Rock Quality

The rock mass quality at the intersection between the cross passage and the parallel running tunnels (or any other underground junction between two separate structures) will have a primary influence upon the means and methods of excavation and initial ground support, and therefore a secondary influence upon the design of the final lining system at the intersection. This secondary influence results from the initial ground support not being expected to carry the full rock loads over the design life of the structure, therefore transferring a fixed percentage of the initial support design rock load to the final lining over time.

3.5.9.2 Influence of Tunnel Depth

At underground intersections (or any other underground junction between two separate structures), an increase in the rock mass stress may produce higher stress concentrations (magnitude of concentrated stress) around the intersection area, for the same geometric and spatial layout of the intersection. Thus the tunnel depth, combined with rock mass quality will together be the prime considerations for initial ground support design, and therefore a contributing factor to the design of the final lining of the cross passage.

3.6 THEORETICAL METHODS OF ANALYSIS

3.6.1 Analysis of Non-Seismic Loads

The structural analysis of a tunnel lining under external and internal loads can be performed using linear analysis methods and computers. The finite element method can be used to incorporate soil-structure interaction. The advantages of the finite element method are:

- Irregular boundaries can be handled with ease;
- Ability to assign different mechanical properties to any region of the surrounding soils;
- Capability to model incremental construction loads.

Tangential and radial springs can be applied at each node of the mathematical model of lining to represent the surrounding soil stiffness and supports. The tangential springs represent the shear stress transmittal between the lining and the surrounding medium. The radial springs can only be used to resist compressive forces. Tensile springs should be ignored or deleted from the mathematical model at regions where tension force in springs may occur.

The radial and tangential spring stiffness used in the beam-spring computer model can be calculated from the following formulas:

$$K_r = E_m\, b\, \varphi/(1+\mu_m) \qquad \text{Eq. 1}$$

for radial spring stiffness,

$$K_t = K_r\, G/E_m = .5\, K_r/(1+\mu_m) \qquad \text{Eq. 2}$$

for tangential spring stiffness.

Where K_r = radial spring stiffness, kips/in.
E_m = young's modulus of the soil, ksi
b = length of tunnel segment, in.
φ = arc subtended by the beam element, radians
μ_m = Poisson's ratio of the soils
K_t = tangential spring stiffness, kips/in.
G = shear modulus of elasticity of the soils, ksi

Soil modulus of elasticity is one of the two most important factors in tunnel lining design (the other one is the lateral soil pressure coefficient); the structural engineer should obtain the soil modulus from the geotechnical investigation report.

The above method of analysis can also be used for tunnels in rock. The differences between tunnels in soil and rock are the loads and in situ medium properties.

3.6.2 Analysis of Seismic Forces

For seismic analysis and seismic design of tunnels see TM 2.10.4 Interim Seismic Design and TM 2.10.5 15% Seismic Design Benchmarks.

3.6.1.1 Empirical Methods

Empirical methods of design are considered appropriate for design of initial ground support but not for the final lining.

3.6.1.2 Stress-Strain Methods

Stress-strain analyses should be two-dimensional and should determine rock stresses, loadings, and displacements around the cavern under all conditions of excavation sequencing. The analysis should account for factors that influence the loads on the excavation. The analysis should include relevant safety factors and the allowable ground movements. The method should use numerical analysis with fully verified software.

The two-dimensional stress-strain method should account for three-dimension effects of excavation progress and the timing of support installation by allowing for release of ground stress prior to the installation of support.

Continuum methods should be used for analysis of underground openings situated in intact rock without joints, or in a rock mass with a joint spacing more than 1/20 of the final span of the excavation. The method should include the influence of joints as an implicit property of rock.

Continuum methods that model individual joint planes may be used to analyze rock block and/or wedge stability, and verify results of the force-equilibrium methods.

Discontinuum methods should be used to analyze the stress-strain behavior of underground openings stated in a rock mass with a mean joint spacing less than 1/20 of the final span of the excavation.

For more complicated intersections between underground openings, three dimensional numerical models should be used.

3.6.1.3 Force Equilibrium Methods

Force equilibrium methods should be used for analysis for the design of initial support for cases governed by stability of discrete blocks and wedges of rock. The analysis should use the joint geometric information presented in the geotechnical reports. The force equilibrium methods should determine the most probable size, location, weight, and shape of blocks that could kinematically fall out of the cavern crown or sidewalls by the action of gravity, under the boundary conditions of the prevailing discontinuity orientations and the in-situ stress conditions. The in-situ stress conditions should be included in the block analyses.

The initial support system should be designed to stabilize the rock blocks that are unstable, including the maximum block or wedge. The calculated bolt forces and shotcrete thickness should be certified by stress-strain methods.

For more complicated intersections between underground openings, three dimensional numerical models should be used.

3.6.3 Dynamic

3.6.2.1 Free Field Deformations

Will be defined in future guidance documents.

3.6.2.2 Soil-Structure Interaction

Will be defined in future guidance documents.

3.6.2.3 Numerical Methods

Will be defined in future guidance documents.

3.6.4 Validation

3.6.3.1 Computer Code Applicability Demonstration

Before any computer models are implemented for use as part of the design process, supporting documentation shall be provided by the designer for review and approval, demonstrating that the software satisfies the requirements of this technical memorandum, is suitable for the ground, groundwater, and seismic conditions to which it will be applied, and that the designer is familiar with and suitably trained for its use.

3.6.3.2 Previous Successful Case History Documentation

Before any computer models are implemented for use as part of the design process, supporting documentation shall be provided by the designer for review and approval, demonstrating that the software has been used successfully in the past on similar projects with similar ground, groundwater, and static and seismic loading conditions.

4.0 SUMMARY AND RECOMMENDATIONS

4.1 GENERAL

This technical memorandum addresses the basic issues related to the structural design of permanent cast-in-place concrete or sprayed concrete liners for mined rock tunnels on the California High-Speed Train Project. These issues include design life, durability, loads and analyses. Related design considerations such as pillar stability, watertightness and drainage are addressed along with the applicability of undrained / drained and reinforced/ unreinforced permanent linings.

Typical initial support arrangements, methods of construction and ground conditions are addressed in so far as they influence the design of the permanent works. Site specific initial support arrangements and methods of construction will depend on local conditions and are to be addressed by each regional consultant. Likewise, the seismic environment is expected to be different at different tunnel sites, requiring an individual site specific assessment by section designers. Ultimately, the design-builder will undertake detailed design, and select methods of construction and initial support requirements.

It is recommended that all tunnels carrying high-speed trains be designed for both static and dynamic loading conditions, including the ability to withstand all anticipated seismic distortions without structure failure. Different tunnel locations along the planned alignment are expected to have different boundary conditions (geology, hydrogeology, topography, and seismic), but they must all satisfy the contractual structural, seismic and durability performance requirements regardless of the site specific boundary conditions.

All tunnels shall be watertight (designed as an undrained tunnel) unless site specific conditions justify the application of a drained structure with the attendant requirements for long term maintenance and operation of the drains that intercept and infiltration seepage water. Such deviations from the basic requirement for an undrained structure must be obtained from the Authority during the design process, based upon site specific considerations and detailed justifications considering all contributing factors, including the long term cost/benefit comparisons between a drained and an undrained structure at the same location, operating under the same set of boundary conditions, and complying with the same design and performance criteria.

Typical initial support, permanent support, waterproofing and drainage requirements for drained, mined single track tunnels in rock are shown on Drawing 2.4.5 – A in Appendix A.

It is recommended that a similar drawing is developed for an undrained rock tunnel.

This document could also be expanded to provide additional guidance to soft ground tunnels and underground structures.

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5.0 SOURCE INFORMATION AND REFERENCES

This Technical Memorandum has drawn on the following documentation in its development:

1. CHSTP Technical Memorandum 1.1.2 - Design Life
2. CHSTP Technical Memorandum 1.1.10 - Structure Gauge
3. CHSTP Technical Memorandum 1.1.21 - Cross Sections for 15% Design
4. CHSTP Technical Memorandum 2.3.2 - Structure Design Loads
5. CHSTP Technical Memorandum 2.4.2 - Basic High-Speed Train Tunnel Configuration
6. CHSTP Technical Memorandum 2.4.6 - High-Speed Train Tunnel Portal Guidelines
7. CHSTP Technical Memorandum 2.4.8 - Service and Maintenance Requirements
8. CHSTP Technical Memorandum 2.9.3 - Geotechnical and Seismic Hazard Evaluation Guidelines
9. CHSTP Technical Memorandum 2.9.6 - Ground Motion for MCE, DBE & LDBE for 30% Design
10. CHSTP Technical Memorandum 2.9.10 - Geotechnical Analysis and Engineering Design Criteria
11. CHSTP Technical Memorandum 2.10 4 - Interim Seismic Design Criteria
12. CHSTP Technical Memorandum 2.10.6 - Fault Crossing Design Guidelines
13. CHSTP Technical Memorandum 3.2.6 - Traction Power Electrification System Requirements for Grounding, Bonding, and Protection From Electric Shock
14. Taiwan High Speed Rail Corporation Civil Works Volume 9 Design Specifications:
    - Section 6 : Tunnel Design Specification
15. CHSTP System Requirements
    - SR 4-02.6 - Facilities for self-rescue, evacuation and rescue in the event of an incident
16. Design Recommendations for Concrete Tunnel Linings - US Department of Transportation 1983 (by Ed Cording and others at University of Illinois)
17. Tunnel Lining Design Guide – British Tunneling Society and Institution of Civil Engineers
18. Japanese Standard for Mountain Tunneling
19. Japanese Standard for Shield Tunneling

6.0 DESIGN MANUAL CRITERIA

This document is intended as guidance for preliminary design and development of performance specifications, and includes references to final design-related work which will be performed in a subsequent design phase by the design-builder. For 30% design, written PMT approval is required where mined tunnels are to be considered prior to the use of the direction and guidance contained in this document. For preliminary design, this document is be used only to the extent necessary to complete the 30% design in accordance with TM 0.1.1 PE (30% Design) Scope Guidelines.

6.1 GENERAL

This document identifies tunnel structural design elements to be considered and evaluated specifically for rock tunnels that are to be used exclusively by high-speed passenger trains. It is particularly focused on the rock tunnels to be constructed through the mountainous terrain of the Pacheco Pass, Tehachapi and San Gabriel ranges and is expected to also be applicable for rock tunnels that are constructed along other segments to the high-speed train alignment.

This document addresses the basic issues pertaining to the structural design of permanent cast-in-place concrete or sprayed concrete linings for mined rock tunnels. The basic structural design parameters are identified for the purpose of confirming technical feasibility and establishing consistent tunnel design elements. These parameters include design life, loads and analyses. Related design considerations such as pillar stability, watertightness and drainage are addressed along with the applicability of undrained/drained and reinforced/unreinforced permanent linings.

This memorandum includes discussion of the following issues:

- Advantages and disadvantages of drained versus undrained rock tunnels, primarily as the drainage option relates to long term operations and maintenance requirements, and the potential increased structural requirements for a tunnel lining to be able to support full hydrostatic groundwater pressures.
- Advantages and disadvantages of reinforced and unreinforced permanent liners.

The structural design requirements are conceptually defined for both static and dynamic loading situations. The requirements are presented conceptually since the requirements must apply to a variety of ground and groundwater conditions as well as to variable topographic conditions. These conditions are anticipated to vary between different tunnel sites and section designers shall develop these generic requirements to be compatible with site specific subsurface conditions. In addition, the seismic environment is expected to be different at different tunnel sites, again requiring an individual site specific assessment by section designers.

From a static loading conditions perspective, the structural design requirements are addressed for both geological and hydro-geological loading conditions.

Typical initial support arrangements, methods of construction and ground conditions are addressed in so far as they influence the design of the permanent works. Site specific initial support arrangements and methods of construction will depend on local conditions and are to be addressed by each regional consultant. Likewise, the seismic environment is expected to be different at different tunnel sites, requiring an individual site specific assessment be section designers. Ultimately, the design-builder will undertake detailed design and select methods of construction and initial support requirements.

Loadings will ultimately be a function of site specific ground conditions, with tunnels penetrating through fault zones (inactive for purposes of this technical memorandum), which may be composed of extremely fractured and/or decomposed materials which are likely to exhibit squeezing ground conditions, the degree being a function of both the character of the fault zone materials and the depth of burial of the tunnel. Over excavation and/or a yielding lining may be required in these conditions.

For seismic considerations, tunnels generally perform better than above-ground structures. Unlike buildings and bridges, tunnels are not inertia-driven and the tunnel deformations are controlled by the displacement of the surrounding soil medium.

6.2 DESIGN CONSIDERATIONS

6.2.1 Tunnel Linings

6.2.1.1 Initial Ground Support

Final design of the initial ground support will be the responsibility of the design-builder, based upon the geotechnical information supplied in the Contract Documents, as well as the design-builder's plans, and means and methods of underground construction. Typical initial support requirements for mined rock tunnels in good and poor quality rock are shown on Drawing 2.4.5 – A in Appendix A.

6.2.1.2 Permanent Ground Support

Permanent ground support for any mined underground excavation shall be designed for the ground and groundwater conditions for all locations within the tunnel or other structure being considered. It must be designed for the full design life of the facility without detrimental effects from external influences such as ground and groundwater loads, ground and groundwater chemistry, topographic conditions, operational conditions, and earthquake motions.

Typical permanent support requirements for drained, mined single track tunnels in rock are shown on Drawing 2.4.5 – A in Appendix A.

Reference TM 2.10.4 – Interim Seismic Design Criteria.

<u>Lining Type</u>

The type of lining to be implemented for any particular mined underground structure will be selected by the design-builder provided that all performance criteria have been demonstrated to have been satisfied during the design process.

Sprayed Concrete

Sprayed concrete (shotcrete) may be used as permanent ground support for any mined underground structure, provided that it satisfies project requirements for long term excavation stability, lining durability, design longevity, lining leakage rate, and all tunnel operational requirements such as train and auxiliary equipment clearances, ventilation, drainage, lighting, fire and life safety.

Cast-in-Place Concrete

Cast-in-place (CIP) concrete may be used as permanent ground support for any mined underground structure, provided that it satisfies project requirements for long term excavation stability, lining durability, design longevity, lining leakage rate, and all tunnel operational requirements such as train and auxiliary equipment clearances, ventilation, drainage, lighting, fire and life safety.

<u>Influence of Ground Conditions</u>

For mined underground excavation, all contributing ground conditions throughout the length of the structure shall be considered, including the potential for wedge instability from intersecting rock mass discontinuities, potential ground squeezing in weak, intensely weathered, or otherwise disintegrated or locally crushed rock mass materials (e.g., in inactive fault zones) from stresses around the excavated opening being higher than the rock mass strength adjacent to the opening (including special zones of increased stresses such as underground intersections) and areas where the excavation width increases such as in cross over caverns, potential running ground conditions when penetrating intensely weathered, or otherwise disintegrated or locally crushed rock mass materials (e.g., in inactive fault zones), and in weathered, altered, or intensely fractured geologic materials in portal zones, including potential loading from surface landslides, rock slides or debris flows originating somewhere above the tunnel portal.

Influence of Groundwater Depth

For mined underground excavation, all contributing groundwater conditions throughout the length of the structure shall be considered, including the potential for seasonal increases in static groundwater levels, long term potential increases in groundwater levels (e.g., future reservoirs to be built above the completed tunnel) perched water above geologic aquitards, and potential variations in groundwater pressure on opposite sides of a geological fault zone.

Permeability of Lining

The permeability of the initial ground support system for any mined underground excavation is not critical, but shall be sufficiently low such that excessive groundwater infiltration through the initial lining does not preclude the successful installation of a waterproofing layer before installation of the final lining (for both undrained tunnels with full waterproofing encapsulation, and for drained tunnels which utilize only an umbrella waterproofing system terminating at the tunnel invert). Water-tightness (permeability) of the initial lining applies to the entire initial lining, including all construction joints, expansion joints, cold joints etc.

The permeability of the final lining shall be sufficiently low in order to comply with the watertightness requirements of the completed structure over the design life of the completed structure, both of which are defined elsewhere. Water-tightness (permeability) of the final lining applies to the entire final lining, including all construction joints, expansion joints, cold joints etc.

Reinforcement of Lining

Reinforcement of the tunnel lining for any mined underground structure shall utilize reinforcing elements that have been demonstrated during the design process to comply with all required design codes and/or applicable regulations, and all project performance criteria. For the final lining, either sprayed concrete (shotcrete) or cast-in-place concrete, reinforcing elements shall provide long term corrosion resistance in order to satisfy the durability requirements over the design life of the structure.

6.2.1.3 Interaction with Initial Support in Design of Permanent Support

The design of the permanent ground support system may assume a contribution of the initial ground support system, based upon its design capacity and the structural components utilized at any point along a tunnel, at cross passages, and in crossover caverns. The method of assessing this capacity shall be approved by the Authority. The general guideline in terms of accepting an initial lining contribution to long term ground support is that only the components of the initial ground support system that may be considered to be “permanent” are those components that can be demonstrated to not be susceptible to long term corrosion and loss of structural capability. These generic criteria would normally exclude all rock reinforcement (unless fully encapsulated in a corrosion protection envelope), and any steel ribs or lattice girders not fully embedded in shotcrete or concrete. Regardless of these general guidelines, each tunnel shall be evaluated independently, and the case made on a site specific basis, for any use of the initial lining contribution to long term ground support.

6.2.2 Loads

6.2.2.1 Static Loads

Static loads to be incorporated in the design of the final lining of all underground structures include all non seismic and non train vibration related loads. These are described in TM 2.3.2 – Structural Design Loads. In addition, any loads that may be introduced by the particular details of the design-builder’s selected means and methods of construction shall be accounted for in the design process.

Earth Loads

Earth loads to be accounted for in the design of the permanent lining of all mined underground structures, shall properly and fully account for all potential geological long term contributing factors such as gravity (assuming some arching as allowed by the site specific ground conditions), rock structure orientations, spacings, and character, natural and structure induces (stress concentrations) stresses in the ground over and adjacent to the underground structure,

and any potential squeezing loads that may be produced by the ground adjacent to the opening being overstressed by the creation of the opening or any adjacent openings (e.g., parallel tunnel) or underground intersections (e.g., cross passages) intersections.

Groundwater Loads

Groundwater loads shall represent the full static groundwater levels to be expected along the tunnel alignment at any particular location along the length of any particular tunnel, unless a drained tunnel is proposed at any particular location. Should a drained tunnel be proposed for “extreme” groundwater conditions that would otherwise require an excessive lining thickness for an undrained structure, the designer shall prepare a proposed reduced lining design water pressure.

6.2.2.2 Dynamic Loads

Dynamic loads to be incorporated in the design of the final lining of all underground structures include all seismic and all train vibration related loads. These are outlined in TM 2.3.2 - Structure Design Loads and TM 2.10.4 - Interim Seismic Design Criteria.

Train Loads

Dynamic loads from trains operation in any underground openings shall be accounted for as required by TM 2.3.2 - Structure Design Loads and TM 2.10.4 - Interim Seismic Design Criteria.

Surcharge Loads

Surcharge loads from any existing or planned structures that overly and/or are adjacent to the mined underground structures, and whose ground pressure (shallow or deep foundations) extends to tunnel location and depth, shall be accounted for in the design of the final lining.

Seismic Loads

Seismic loads to be considered in the design of the final lining of all underground structures shall be in compliance with the requirements presented in TM 2.3.2 - Structure Design Loads and TM 2.10.4 - Interim Seismic Design Criteria. It shall also be a design requirement that all anticipated seismic distortions to both underground and portal structures resulting from a “design earthquake” shall be evaluated for structural stability for that level of performance per the requirements of TM 2.10.4.

6.2.3 Load Combinations

Load combinations to be considered in the design of final linings for all mined underground structures are as defined in TM 2.3.2 - Structure Design Loads.

6.2.3.1 Applicable Codes

Design codes applicable to the design of final linings for all mined underground structures are as defined in TM 2.10.4 - Interim Seismic Design Criteria.

6.2.4 Geometric Considerations

6.2.4.1 Tunnel Fixed Equipment

Tunnels are required to provide sufficient provide space for all necessary fixed equipment.

Conceptual design drawings have been developed to illustrate various types, and typical arrangement and locations of continuous and intermittent fixed equipment and the supporting tunnel structure. These drawings are included in TM 2.4.2 - Basic Tunnel Configuration and should be read in conjunction with typical tunnel cross sections included in TM 1.1.21 - Typical Cross Sections. Arrangements and locations will vary at tunnel enlargements, niches, cross passages and interfaces with other tunnel and structural sections.

6.2.4.2 Tunnel Clearances

The tunnels are required to allow sufficient clearances for all necessary fixed equipment and rolling stock.

Dimensions for static and dynamic envelopes in the tunnels are the same as for other structures and development is documented in TM 1.1.10 - Structure Gauge.

For design and performance requirements with respect to tunnel clearances, see TM 2.4.2 – Basic Tunnel Configuration for reference.

6.2.4.3 Tunnel Size

For design and performance requirements with respect to tunnel size, see TM 2.4.2 – Basic Tunnel Configuration for reference.

6.2.4.4 Tunnel Shape

For design and performance requirements with respect to tunnel cross section shape see TM 2.4.2 – Basic Tunnel Configuration for reference.

6.2.4.5 Invert Requirements

For mined structures where a non-circular invert shape is considered, stress concentrations may occur in the lining at locations of perimeter geometry such as the invert where the sidewall perimeter profile merges with the invert profile. If in the preliminary design of the initial and final lining, the combination of ground and groundwater loads applied to the structure, create excessive stress concentrations in the lining at this merge point between perimeter profiles, the lining shape may need to be modified to reduce these stresses to an acceptable level. This may have particular application where squeezing ground is considered, with high horizontal pressures and potential invert heave, and/or where an undrained lining has hydrostatic groundwater pressures that are sufficiently high to produce similar stress concentrations.

6.2.5 Watertightness and Drainage

6.2.5.1 Considerations

A number of factors shall be considered when evaluating the watertightness and drainage aspects of any particular mined underground structure, as outlined below.

<u>Groundwater Depth</u>

The height of the static groundwater level above the tunnel crown, including any anticipated seasonal and/or long term variations, shall be considered in making the determination and/or recommendation of whether or not a mined underground should be designed as a drained structure or an undrained structure. Factors that contribute to this determination/recommendation shall include but not be limited to:

- Rock mass permeability and risk of long term groundwater drawdown for a drained structure.
- Recharge rate to the underground hydro-geological regime from surface precipitation.
- Magnitude of the long term groundwater pressure that must be designed for, and the structural requirements (and related cost implications) to resist this “design” groundwater pressure.
- Site specific groundwater (and ground) chemistry, and its related potential for clogging of drainage features with calcium precipitates over the design life of the mined underground facility.
- The possible presence of dissolved toxic or explosive gases that could be released into the tunnel environment should the groundwater be present within the operational tunnel features for a drained tunnel.
- Long term operations and maintenance considerations (both effectiveness and cost) for a drained tunnel, considering the groundwater chemistry (and initial tunnel lining chemical dissolution potential) and its potential for excessive carbonate buildup in the drainage system. A cost benefit analysis shall be performed in order to help in making lining drainage requirement determinations, in cases where only marginal benefits would be gained by the requirement for an undrained final lining for a particular mined underground structure.

Groundwater Chemistry

It shall be a requirement that groundwater chemistry be considered during the design process, as it may influence the design and the long term performance characteristics of the waterproofing and drainage provisions of tunnels. Although all dissolved solids and gases in the groundwater shall be evaluated and considered, of particular concern for design of the waterproofing and drainage system is the presence of dissolved calcium carbonate, which can come out of solution due to changes in pressure and/or temperature as groundwater passes into the drainage system, often complicated by contact of the infiltrating groundwater with air and/or the loss of carbon dioxide in the process. In such conditions, the calcium carbonate forms a precipitate on any contact surfaces, and the clogging potential for this precipitate on waterproofing and drainage components of the final lining design shall be fully evaluated and accounted for in the design. A related phenomenon is the leaching of calcium carbonate out of porous construction materials such as shotcrete or concrete as the groundwater passes through them. This process is a function (in addition to the other factors noted above) of the carbon dioxide content, the pH, both of which influence the solubility of calcium carbonate in water, This potential leaching process shall also be evaluated in the design process, and accounted for in the design details of the waterproofing and drainage system components.

Dissolved Gases

The potential for the presence of dissolved noxious or explosive gases dissolved in the groundwater at any particular tunnel site shall be evaluated as part of the detailed subsurface investigation. If a positive gas presence indication is determined, then the waterproofing system shall also be impermeable to the passage of gases through the waterproofing system. Also, if a positive gas presence is determined, then only an undrained tunnel design shall be considered acceptable, to prevent the possibility of noxious or explosive gases ever entering the operating tunnel.

6.2.5.2 Requirements

Waterproofing

Waterproofing as a critical component of the final lining of any mined underground structure will be required for all such structures. The determination whether or not this waterproofing shall provide full or partial encapsulation will be a function of the decision on the requirement for a drained or an undrained final lining. A drained final tunnel lining would require only umbrella waterproofing over the top arch, invert to invert. An undrained final tunnel lining would require full encapsulation by the waterproofing layer.

Typical waterproofing arrangements for drained, mined single track tunnels in rock are shown on Drawing 2.4.5 – A in Appendix A.

For any waterproofing system, whether it is the drained umbrella system or the undrained full encapsulation system, the waterproofing system shall be compartmentalized by water barriers incorporated into the waterproofing membrane, installed at intervals ≤165 feet. Waterproofing and drainage materials applied to the exposed surface of the initial lining system shall be flame-proof for safety. The membrane shall incorporate a colored embedded ”tell-tale” layer to reveal any membrane penetrations made during final lining reinforcement placement, so that they can be repaired before the final lining is placed.

Drainage

For an undrained final tunnel lining, no separate leakage-specific in-tunnel drainage system will be required. Any minor amount of groundwater infiltration through the final tunnel lining, if in compliance with the project leakage limits as defined below, can be handled by the inside tunnel drainage system, which will be designed to collect and divert, watershed of trains when passing through the tunnel, outside precipitation draining into the tunnel from the portal areas, and water (or foam chemicals) used in emergency response to a fire incident within the tunnel.

The minimum incline of drainage systems shall be ≥0.3% towards a portal. The minimum drain pipe diameter shall be 12 inches. Drains shall be accessible for maintenance and cleaning at

intervals ≤165 feet. Longitudinal drains for tunnel water shall be placed at the low point of the invert.

For a drained tunnel, a separate use specific drainage system at the case of the tunnel arches, shall be designed to collect and divert all infiltrating seepage water which has been diverted to the invert drains by the umbrella waterproofing system.

Typical drainage arrangements for drained, mined single track tunnels in rock are shown on Drawing 2.4.5 – A in Appendix A.

6.2.5.3 Maintenance Implications

Drained versus Undrained

There are several factors to be considered when making the decision about whether or not a final tunnel lining should be drained or undrained. These factors include but are not limited to initial construction cost, long term operations and maintenance costs, potential water drawdown, and potentially increased structural requirements resulting from the requirement to design for full hydrostatic water pressures. The reliable functioning of tunnel waterproofing is particularly important for transportation tunnels due to the access restrictions for inspection and maintenance during tunnel operations. A waterproofing system must represent the optimal solution between the desired performance requirements, and the technical and economic considerations. In many cases, the cheapest solution may not represent the most economical one, once operations and maintenance costs over the life of the structure are considered. The relatively low additional costs of a good waterproofing system usually have a positive effect over the life of the structure.

The concern for groundwater drawdown is a concern for many projects where drained tunnels are either planned or built. For a drained tunnel with a low leakage rate, the groundwater drawdown influence zone may be small, even though the tunnel functions as a drain, albeit a “slow” drain. Considering the above discussions, it should noted, that even if a drained tunnel does draw down the static groundwater level, that drawdown has limits to its influence zone as with conventional drawdown. All of these technical considerations shall be included as part of the overall design/decision process when deciding whether a tunnel should be drained or not.

Influence of Groundwater Chemistry

It is a common problem in many tunnels, that there is a clogging risk of tunnel drainage systems due to the deposition of calcium carbonate deposits. Systematic tunnel inspections over the early years of tunnel operations for several transit systems has revealed that tunnel waterproofing and drainage were critical, with potential threats to tunnel stability as tunnel drains became clogged with calcium carbonate deposits building up over time in the drainage system, with consequent build-up of hydrostatic pressures on the tunnel lining when the tunnel had been initially designed as a “drained” structure. One of the primary conclusions was that the inclusion of a drainage fabric layer in the lining of a sequentially mined tunnel (SEM or NATM) could be a key element in keeping hydrostatic water pressures under control for structures designed to be “drained”, provided that the drainage system could be kept open and operational over the life of the structure. It shall therefore be a design requirement that long term maintenance implications resulting from potentially adverse groundwater chemistry, be fully evaluated so that the waterproofing and drainage design elements reflect provisions to minimize long term maintenance requirements and related operational costs.

Cost Implications

As a consideration in the decision process of having a drained versus an undrained tunnel it is inevitable that cost will be a driving force (in addition to technical factors), if not the determining factor. Cost considerations during the design evaluations shall include not only the initial capital cost of construction, but also the long term costs of operations and maintenance, which can be considerable if the drainage system of a drained tunnel require frequent cleaning. Another cost consideration, although it is an intangible cost, is the cost of disruption of tunnel service if the tunnel must be closed, or have limited shut-down periods, in order to allow the maintenance and cleaning of the tunnel drainage system to be performed. The higher construction costs of an undrained tunnel often constitute an argument in favor of the decision to build a drained tunnel

instead. Additional cost considerations, which shall be considered when making the design exception decision about the type and extent of tunnel drainage, are noted below:

- A substantial part of the expenses of tunnel maintenance and repair are a result of mistakes and errors during design and construction.
- Over the service life of a tunnel, the required efforts for tunnel maintenance resulting from the adoption of a drained waterproofing system can become quite large. The performance of a Life Cycle Cost analysis for both tunnel drainage options sometimes concludes that, in spite of the higher initial construction costs, an undrained tunnel is the more cost effective overall solution.
- The higher maintenance costs of drained tunnels are usually attributable to the build-up of calcium deposits in the drainage piping system, requiring a high level of both technical effort and logistical planning for an operational tunnel.
- The problem of drainage pipe calcification is often amplified by design and construction decisions and actions such as: use of unsuitable drainage materials, poor quality control and inspection when installing the drainage system, and unsuitable inspection and maintenance methods and unfavorable maintenance intervals.
- Significant factors which contribute to the development of increased tunnel operational costs include: the systematic removal of carbonate build-up increases the cost of tunnel operations, the service life of the drainage pipes may be reduced due to the abrasive action of the cleaning methods and/or tools, the periodic requirement to temporarily close a tunnel to allow systematic maintenance operations to take place.

6.2.5.4 Acceptable Leakage Rates

<u>Short Term</u>

Short term groundwater infiltration rates as they apply to the design of the final lining, will be related primarily to allowable seepage through the initial tunnel lining, and its impact upon the ability to install the final waterproofing layers on the initial tunnel lining before installation of the final tunnel lining. Such infiltration rates will be as determined by the manufacturer’s recommendations for the particular waterproofing materials being considered at any particular tunnel.

<u>Long Term</u>

The allowable long term seepage through the final tunnel lining has not yet been determined. Underground connecting facilities such as cross passages are required to satisfy the same watertightness criterion as the mainline tunnels.

6.2.6 Pillar Stability

6.2.6.1 Influence of Rock Quality

Rock quality can have a major impact upon pillar stability, with lower rock mass quality having lower rock mass strength. This potential must be considered when evaluating pillar stability between parallel running tunnels, especially where the pillar is less than one excavated diameter in width, and where the overburden is relatively high, and where the ground may be weak due to poor induration, weathering, intense fracturing or crushing, etc. In such weak ground conditions, increased pillar reinforcement may be required during construction, and the potential impact of these weak ground conditions upon the final tunnel lining shall be checked and fully accounted for during detailed design.

6.2.6.2 Influence of Discontinuity Patterns and Characteristics

Even if the rock mass is of relatively good quality, rock mass discontinuities may form potentially loose wedges that if allowed to displace out of the pillar, reduce the pillar overall strength sue to the reduction in bearing area. This potential must be considered when evaluating pillar stability between parallel running tunnels, especially where the pillar is less than one excavated diameter in width, and where rock mass discontinuities are well established and form kinematically possibly

wedge failures. In some cases, it may be required to install pre-support in the pillar from the first tunnel, before driving the second tunnel, so that concentrated loads from loose wedges do not come on the final lining.

6.2.6.3 Influence of Tunnel Size

As tunnels get wider, especially as poor ground is encountered, the excavation size usually increases in order to allow more robust initial ground support, and final lining to be installed without infringing upon the operational train clearances within the tunnel. This becomes a more critical issue as the track spacing between tunnels remains the same, but the tunnel excavations become wider. The potential for overstressing the central pillar under such conditions shall be fully accounted for in the development of the required means and methods of construction, and the potential impact of these means and methods upon the performance of the final tunnel lining.

6.2.6.4 Influence of Tunnel Spacing

For a fixed spacing between track centerlines, the pillar width between the excavated perimeter surfaces of the two parallel tunnels, should “normally” be kept at a minimum of the equivalent of one excavated tunnel width. Even with this minimum width, the vertical stress concentrations of the two tunnels overlap, creating vertical stresses in the pillar higher than they would have been for an individual tunnel. This is especially critical where the ground may be weak as in fault zones, producing a relatively weak pillar; and/or where the tunnels have a high overburden producing high stresses in the central pillar regardless of pillar strength. Where either or both of these conditions apply, the track spacing and pillar spacing shall be checked to validate whether or not the planned tunnel spacing is wide enough to permit excavation of both tunnels without inducing a pillar collapse and/or tunnel failure. The long term loads on the final tunnel lining, resulting from such a potential pillar failure, shall be fully accounted for in the detailed design process.

6.2.6.5 Influence of Tunnel Depth

For longer tunnels, with potential increasingly high overburden above the tunnels, the influence of these high overburden loads shall be fully accounted for in the design of the final tunnel lining. This would be especially critical where the ground in the central pillar may be weak, intensely fractured, or otherwise unable to carry loads without supplemental ground support. Under these conditions, the long term loads on the final tunnel lining, resulting from potential high pillar stresses, shall be fully accounted for in the detailed design process.

6.2.6.6 Influence of Intersections

Where tunnels are of sufficient length that NFPA fire-life safety regulations require cross passages between adjacent parallel running tunnels. Under these circumstances, the introduction of the cross passage further complicates the stress distribution in the pillar, with even higher stresses in the pillar adjacent to the pillar cross passage, than the pillar without the cross passage. In addition, the creation of the cross passage introduces an additional free face, toward which unstable wedges could fail, under the driving forces of the increased stress concentrations at the tunnel – cross passage intersection. During the design process, the potential failure mechanisms during cross passage excavation, shall be evaluated, and construction means and methods developed to preclude failure, and cross passage linings designed to withstand all induced loads resulting from the three dimensional stress concentrations at the intersection. In addition, the final tunnel lining requirements adjacent to the cross passage intersection shall be checked for satisfactory performance under the potential increased loading resulting from the presence of the cross passage intersection.

6.2.6.7 Acceptable Factor of Safety

<u>Calculation of Pillar Strength</u>

Pillar strength evaluations at any particular place along a tunnel alignment, shall consider all contributing parameters, including but not limited to pillar geometry (W/H), rock type, rock mass discontinuities (orientation, spacing and frequency), degree of weathering, etc.

Calculation of Pillar Stress

Stress calculations in the central pillar between adjacent running tunnels at any particular location along a tunnel alignment, shall consider all contributing parameters, including but not limited to pillar width, overburden depth, underground intersections, surcharge loads, etc.

Construction Term versus Long Term

The Factor of Safety against failure of the central pillar between adjacent running tunnels at any particular location along a tunnel alignment, shall consider the applied stresses at that location, as well as the pillar strength at that location.

6.2.7 Portal Stability

6.2.7.1 Influence of Nearby or Overlying Construction

The design of the portal for any particular tunnel shall consider the potential influence of any existing or planned overlying and/or adjacent structures over the portal, and the portal design m shall accommodate any loadings from these nearby structures.

6.2.7.2 Influence of Rock Type

The design of the portal structure for any particular tunnel shall consider in detail, the type geological conditions in which the portal will be constructed. As a minimum, the portal structure evaluations shall consider such issues such as:

- Rock and/or soil type
- Influence of near surface weathering upon strength and deformation properties of portal zone geological materials
- Influence of discontinuity patterns and characteristics upon slope stability
- Rock-fall considerations and protection requirements above the portal
- Landslide and surficial debris flow risk above the portal

6.2.7.3 Influence of Near Surface Weathering

The in-situ weathering upon portal cut stability at any particular portal site shall be fully evaluated in the design process, considering such factors such as rock type, topography, and surface and subsurface drainage. The extent of and the depth of weathering shall be considering in developing the required depth of the portal cut and the long term stability of the slope above the portal cut.

6.2.7.4 Influence of Discontinuity Patterns and Characteristics

The influence of rock mass discontinuity patterns, spacing, and characteristics, upon portal cut stability at any particular portal site shall be fully evaluated in the design process, considering such factors such as rock type, topography, and surface and subsurface drainage. The extent of and the depth of weathering shall be considering in developing the required depth of the portal cut and the long term stability of the slope above the portal cut. The evaluations shall include both static and dynamic loading conditions.

6.2.7.5 Rock-Fall Considerations and Protection Requirements

The possibility of the localized failure and/or loosening of individual rock blocks (by sliding [planar or wedge] and/or toppling) above the tunnel portal structure shall be evaluated. If such a risk is identified as being plausible, design and construction provisions shall be developed during the design process for stabilization of such potentially loosened blocks. Solutions may include but not be limited to some combination of block removal, tie backs, rock-fall safety nets, trenches, and improved surface water drainage (collection and diversion of runoff away from the portal structure). The evaluations shall include both static and dynamic loading conditions.

6.2.7.6 Landslide and Surficial Debris Flow Risk

The possibility of the localized failure and/or creep of near surface geological materials above the tunnel portal structure shall be evaluated. These types of failure potential shall include but not be limited to landslides (new or reactivated), debris flows, lateral spreading, and localized slumping,

or some combination of these failure mechanisms, If such a risk is identified as being plausible, design and construction provisions shall be developed during the design process for stabilization of such potentially threatening earth instability. Solutions may include but not be limited to some combination of block removal, tie backs, rock-fall safety nets, collection trenches, and improved surface water drainage (collection and diversion of runoff away from the portal structure). The evaluations shall include both static and dynamic loading conditions, and the potential influences of short and long term precipitation events that could increase the pore pressures within the potentially loose earth mass, and thereby reduce the factor of safety against failure.

6.2.7.7 Minimum Rock Cover

The minimum acceptable rock cover over the portal structure shall be ½ tunnel diameter, unless the topography is so flat that such a geometric criterion is impractical. In such a case, each site shall be considered separately as a "special case". In all cases, the portal zone is likely to be in more weathered near surface materials, which are inherently weaker than intact unweathered rock. These "weaker" materials shall be characterized on a site specific basis, and detailed evaluations made with respect to potential slope instability when the portal cut is made. Any potential risk of slope instability shall be remedied by appropriate earth reinforcing systems that provide an adequate Factor of Safety for both static and dynamic loading conditions.

6.2.7.8 Potential Ground Surface Settlement

It is common experience that more lost ground during tunneling occurs at the start of excavation operations, especially in weak and/or weathered materials, typical of what may be expected at the tunnel portal turn-under where actual tunnel excavation will begin. This will be critical for installation of initial ground support, but if loosening of the ground is allowed to develop during the excavation process, then the increased loading will have to be carried, at least in part, by the final tunnel lining. If such loosening and/or excessive lost ground resulted in the development of a chimney to the surface in the portal area, the final lining may be required to carry full overburden loads, depending upon the geological conditions and the methods of remediation of the chimney and the accompanying ground surface settlement.

6.2.7.9 Sidehill Unbalanced Loading

In the event that the topographical restrictions, combined with track alignment requirements will not allow the portal to be aligned near parallel to the sidehill contours, a portal at a skewed angle to the sidehill contours may be produced as a compromise. In such a case, asymmetrical loading on the tunnel portal area may be a result, and this adverse situation shall be analyzed for this loading situation, and any special requirements for sidehill reinforcement incorporated into the portal design in order to reduce or eliminate the unbalanced loading conditions.

6.2.7.10 Influence of Seismic Loading (Shaking and/or Distortion)

Seismic design criteria for all tunnel structures are addressed in TM 2.10.4 - Interim Seismic Design Criteria. The design of the tunnel portal structures and final tunnel lining, and the design of a seismic joint between the portal structure and the buried tunnel structure, shall be in compliance with the requirements of these TMs, including the evaluation of the dynamic slope stability for slopes above the portal structures, and the design of appropriate earth retaining systems under seismic loading conditions. At the structural connection between the buried tunnel structure, and the exposed portal structure, a seismic joint shall be designed and constructed, in order to accommodate any differential ground movements during an earthquake, between the buried structure and the portal structure. This connection shall be able to accommodate any combination of the longitudinal displacement (compression or tension), shear displacement (any direction in a plane perpendicular to the tunnel alignment), and torsional rotation (any direction in a plane perpendicular to the tunnel alignment, between the two adjacent tunnel structures. The amount of each type of displacement to be accommodated by the seismic joint, and the potential combination of movements, shall be based upon a site specific evaluation at each individual tunnel, accounting for the ground conditions and anticipated ground behavior at that tunnel location, and the estimated ground motions to be experienced by the tunnel and portal structures from the "design earthquake" at that particular tunnel. The seismic joint shall be constructed of appropriate materials to satisfy all contractual longevity requirements, as well as being able to

accommodate the estimated differential ground motions without material rupture or other distress that would limit its subsequent ability to perform its intended seismic function.

6.2.7.11 Influence of Surface Water Drainage and Vegetation Cover

Surface waste drainage from above and beside the tunnel portal shall be collected and diverted away from the portal structure, and shall be implemented in such a fashion as to minimize surface erosion, utilizing vegetation plantings if required to reduce erosion potential.

6.2.7.12 Influence of Train Aerodynamics

The details of portal design as a function of train operations (provisions for sonic boom, tunnel length influence, and length of the pressure relief structure) are addressed in TM 2.4.6 Tunnel Portal facilities and TM 2.4.2 Basic Tunnel Configuration.

6.2.7.13 Influence of Topography

The portal area shall be graded as closely as possible to match the pre-construction contours, and the tunnel portal structure shall be as close as possible parallel to the post-construction ground contours.

6.2.8 Crossover Caverns

6.2.8.1 General Considerations

The requirement for crossover structures between adjacent tracks will be a function of the final track alignment developed during the design process, considering contributing factor such as space available for crossovers outside the tunnels, which may be limited in some cases where a viaduct aerial structure connects directly to a tunnel without any at-grade track alignment in between. In such a condition, the track crossover may be required to be underground, incorporated into the tunnel structure. Where the planed twin parallel single track tunnels are utilized, this would require that the two tunnels merge into a single structure without the benefit of a central rock pillar for structural stability. This will require that the larger underground opening be designed for the same operational and performance criteria as for the single track tunnels, and for the site specific boundary conditions (geology, hydrogeology, topography, and seismic) applicable at the tunnel where the underground crossover structure is required. The development of the detailed design of the final lining of the enlarged structure shall account for the size influences of contributing geotechnical factors including but not limited to rock mass quality in the crossover area, overburden depth over the crossover, groundwater height above the crossover, required track spacing and related required opening width to achieve the required rolling stock clearances with the excavation perimeter, and the three dimensional stress influences of the twin tunnel intersections at each end the enlarged single crossover excavation.

6.2.9 Cross Passages

6.2.9.1 Influence of Rock Quality

The rock mass quality at the intersection between the cross passage and the parallel running tunnels (or any other underground junction between two separate structures) will have a primary influence upon the means and methods of excavation and initial ground support, and therefore a secondary influence upon the design of the final lining system at the intersection. This secondary influence results from the initial ground support not being expected to carry the full rock loads over the design life of the structure, therefore transferring a fixed percentage of the initial support design rock load to the final lining over time.

6.2.9.2 Influence of Tunnel Depth

At underground intersections (or any other underground junction between two separate structures), an increase in the rock mass stress may produce higher stress concentrations (magnitude of concentrated stress) around the intersection area, for the same geometric and spatial layout of the intersection. Thus the tunnel depth, combined with rock mass quality will together be the prime considerations for initial ground support design, and therefore a contributing factor to the design of the final lining of the cross passage.

6.3 THEORETICAL METHODS OF ANALYSIS

6.3.1 Analysis of Non-Seismic Loads

The structural analysis of a tunnel lining under external and internal loads can be performed using linear analysis methods and computers. The finite element method can be used to incorporate soil-structure interaction. The advantages of the finite element method are:

- Irregular boundaries can be handled with ease;
- Ability to assign different mechanical properties to any region of the surrounding soils;
- Capability to model incremental construction loads.

Tangential and radial springs can be applied at each node of the mathematical model of lining to represent the surrounding soil stiffness and supports. The tangential springs represent the shear stress transmittal between the lining and the surrounding medium. The radial springs can only be used to resist compressive forces. Tensile springs should be ignored or deleted from the mathematical model at regions where tension force in springs may occur.

The radial and tangential spring stiffness used in the beam-spring computer model can be calculated from the following formulas:

$$K_r = E_m\, b\, \varphi/(1+\mu_m) \qquad \text{Eq. 1}$$

for radial spring stiffness,

$$K_t = K_r\, G/E_m = .5\, K_r/(1+\mu_m) \qquad \text{Eq. 2}$$

for tangential spring stiffness.

Where K_r = radial spring stiffness, kips/in.
E_m = young's modulus of the soil, ksi
b = length of tunnel segment, in.
φ = arc subtended by the beam element, radians
μ_m = Poisson's ratio of the soils
K_t = tangential spring stiffness, kips/in.
G = shear modulus of elasticity of the soils, ksi

Soil modulus of elasticity is one of the two most important factors in tunnel lining design (the other one is the lateral soil pressure coefficient); the structural engineer should obtain the soil modulus from the geotechnical investigation report.

The above method of analysis can also be used for tunnels in rock. The differences between tunnels in soil and rock are the loads and in situ medium properties.

6.3.2 Analysis of Seismic Forces

For seismic analysis and seismic design of tunnels see TM 2.10.4 Interim Seismic Design and TM 2.10.5 15% Seismic Design Benchmarks.

6.3.1.1 Empirical Methods

Empirical methods of design are considered appropriate for design of initial ground support but not for the final lining.

6.3.1.2 Stress-Strain Methods

Stress-strain analyses should be two-dimensional and should determine rock stresses, loadings, and displacements around the cavern under all conditions of excavation sequencing. The analysis should account for factors that influence the loads on the excavation. The analysis should include relevant safety factors and the allowable ground movements. The method should use numerical analysis with fully verified software.

The two-dimensional stress-strain method should account for three-dimension effects of excavation progress and the timing of support installation by allowing for release of ground stress prior to the installation of support.

Continuum methods should be used for analysis of underground openings situated in intact rock without joints, or in a rock mass with a joint spacing more than 1/20 of the final span of the excavation. The method should include the influence of joints as an implicit property of rock.

Continuum methods that model individual joint planes may be used to analyze rock block and/or wedge stability, and verify results of the force-equilibrium methods.

Discontinuum methods should be used to analyze the stress-strain behavior of underground openings stated in a rock mass with a mean joint spacing less than 1/20 of the final span of the excavation.

For more complicated intersections between underground openings, three dimensional numerical models should be used.

6.3.1.3 Force Equilibrium Methods

Force equilibrium methods should be used for analysis for the design of initial support for cases governed by stability of discrete blocks and wedges of rock. The analysis should use the joint geometric information presented in the geotechnical reports. The force equilibrium methods should determine the most probable size, location, weight, and shape of blocks that could kinematically fall out of the cavern crown or sidewalls by the action of gravity, under the boundary conditions of the prevailing discontinuity orientations and the in-situ stress conditions. The in-situ stress conditions should be included in the block analyses.

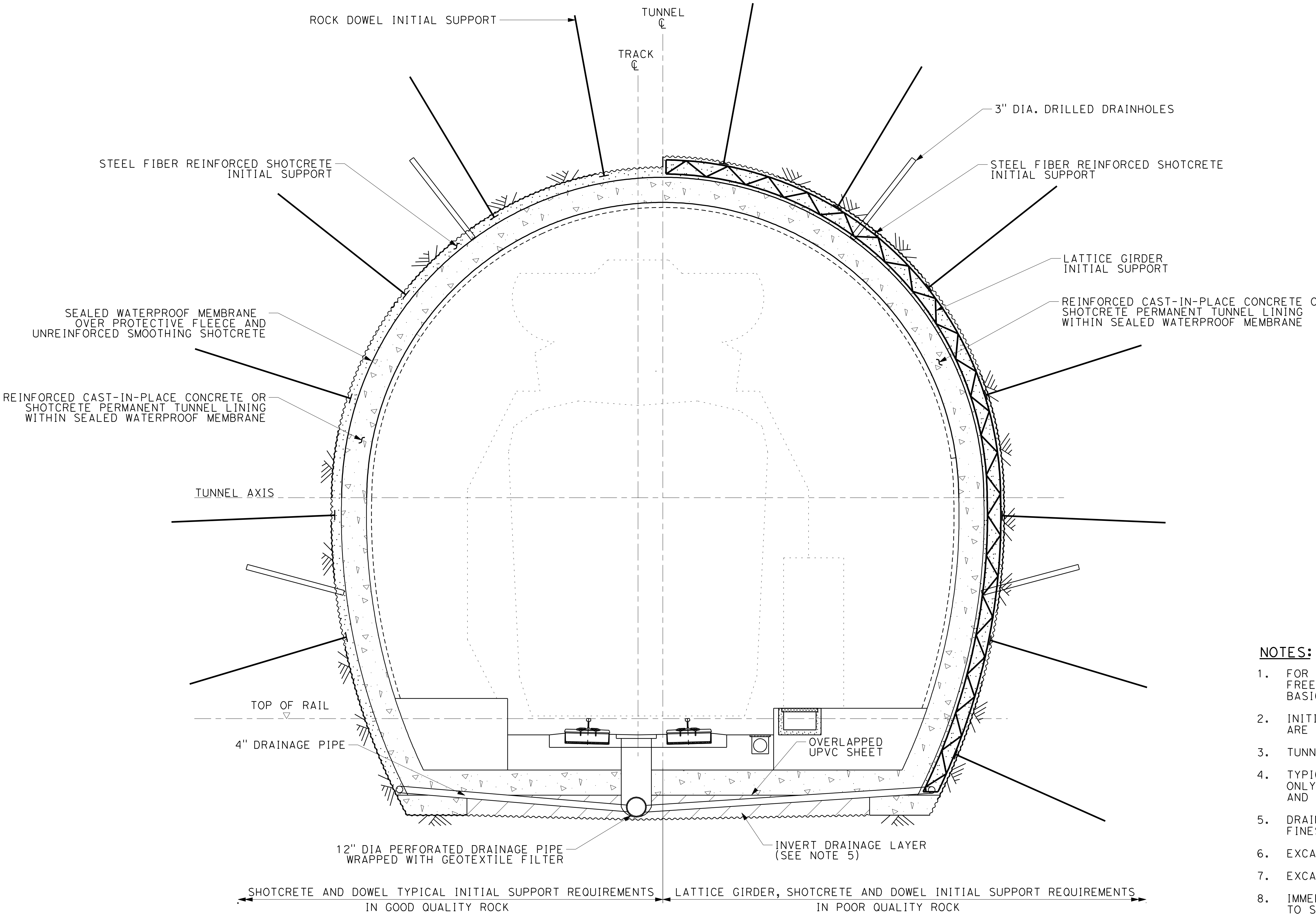
The initial support system should be designed to stabilize the rock blocks that are unstable, including the maximum block or wedge. The calculated bolt forces and shotcrete thickness should be certified by stress-strain methods.

For more complicated intersections between underground openings, three dimensional numerical models should be used.

APPENDICES

APPENDIX A

Drawing TM 2.4.5 – A, Single Track Mined Rock Tunnel, Typical Cross Section (Drained)



TYPICAL CROSS SECTION - DRAINED ROCK TUNNEL

NOTES:

1. FOR TUNNEL INTERNAL DIMENSIONS AND REQUIRED FREE TUNNEL CROSS SECTIONAL AREAS SEE TM 2.4.2 BASIC TUNNEL CONFIGURATIONS.
2. INITIAL SUPPORT AND PERMANENT STRUCTURAL ELEMENTS ARE NOT DESIGNED.
3. TUNNEL SHAPE IS INDICATIVE ONLY.
4. TYPICAL CROSS SECTION FOR DRAINED, MINED, ROCK TUNNELS ONLY. NOT SUITABLE FOR BORED OR UN-DRAINED ROCK TUNNELS AND SOFTGROUND TUNNELS.
5. DRAINAGE LAYER TO BE POROUS CONCRETE OR APPROVED. NO FINES, CLEAN CRUSHED ROCK.
6. EXCAVATED FACE SUPPORT REQUIREMENTS NOT SHOWN.
7. EXCAVATION SEQUENCE AND NUMBER OF HEADINGS NOT SHOWN.
8. IMMEDIATE INSTALLATION OF INITIAL SUPPORT IS CRITICAL TO STABILITY AND SAFETY IN POOR QUALITY ROCK.

3 2 1 0 2 4
3/8"=1'-0"

REV	DATE	BY	CHK	APP	DESCRIPTION

DESIGNED BY: D. McALLISTER
DRAWN BY: D. SOLTERO
CHECKED BY: J. THOMPSON
IN CHARGE: J. CHIRCO
DATE: 06/30/10

PARSONS BRINCKERHOFF

CALIFORNIA HIGH-SPEED RAIL AUTHORITY
FLYCALIFORNIA
Without ever leaving the ground.

CALIFORNIA HIGH-SPEED TRAIN PROJECT

HIGH-SPEED TRAIN TUNNEL STRUCTURES
SINGLE TRACK MINED ROCK TUNNEL
TYPICAL CROSS SECTION (DRAINED)

CONTRACT NO. 13259
DRAWING NO. TM 2.4.5-A
SCALE AS SHOWN
SHEET NO.